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Memristive Crossbar Arrays for Convolutional Neural Network

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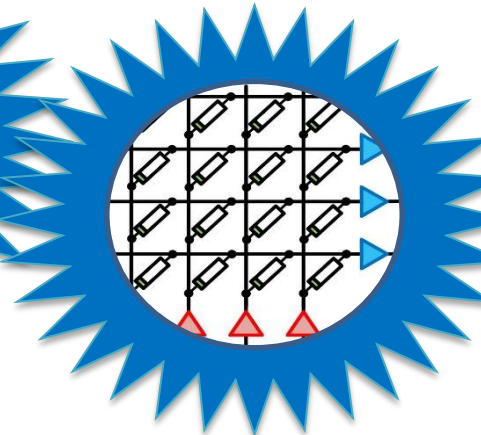
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Low-Cost CNN for IoT

Internet of Things
& Wearable

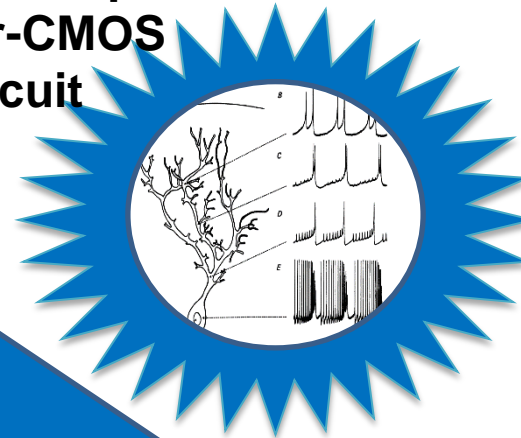


Low-Cost CNN



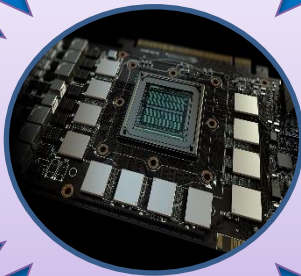
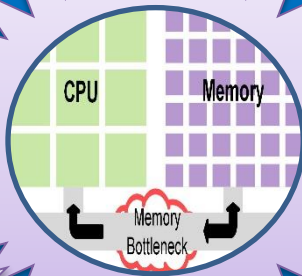
Array
Computation

Event-driven operation w/
Memristor-CMOS
Hybrid circuit



High-Cost CNN

Von Neumann
(Memory Bottleneck)



GPU
(Matrix
Multiplication)

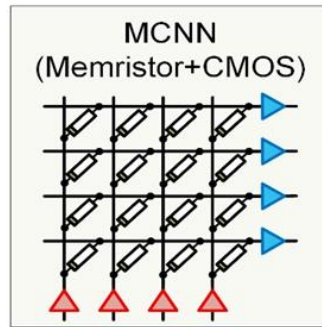
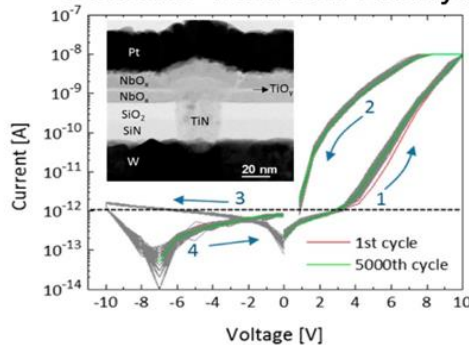


Cloud
Computing

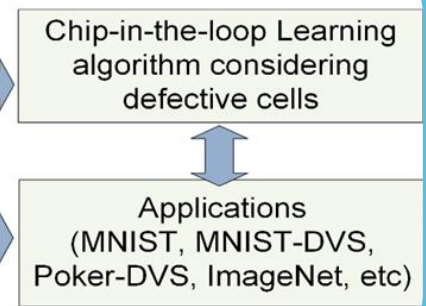
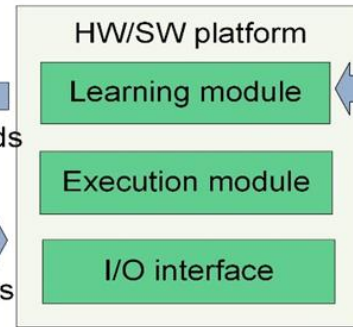
Goal of this work: Memristive Convolutional Neural Network (MCNN)

- ✓ Material/process/device: Self-rectifying/neurotransmitter-mimicking memristor array
- ✓ Circuit/system: Basic building blocks, HW/SW platform, and learning algorithm
- ✓ Applications: MNIST, MNIST-DVS & Poker-DVS (Event-driven), ImageNet (Color), etc

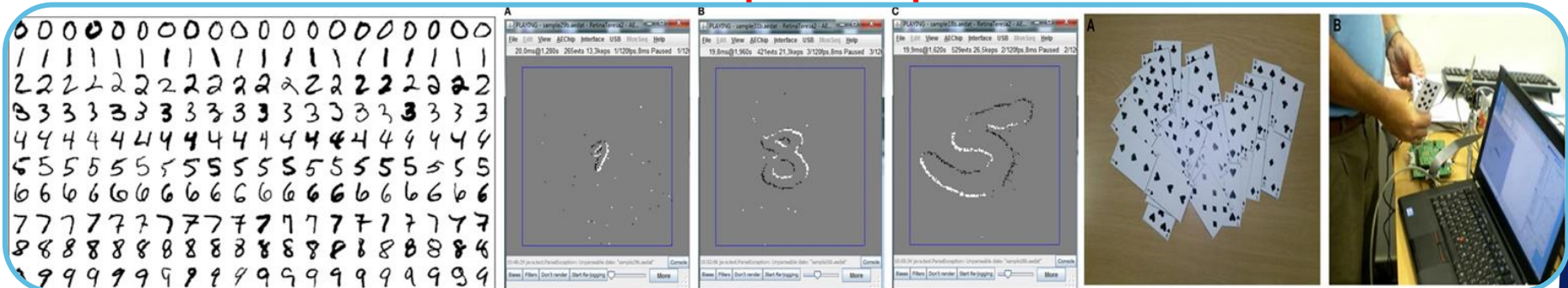
Selector-free/self-rectifying



Commands
Messages



Neuromorphic Computer



MNIST

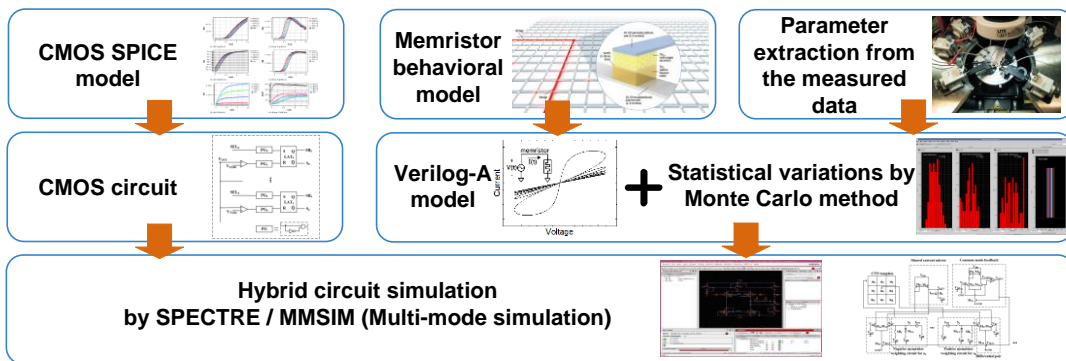
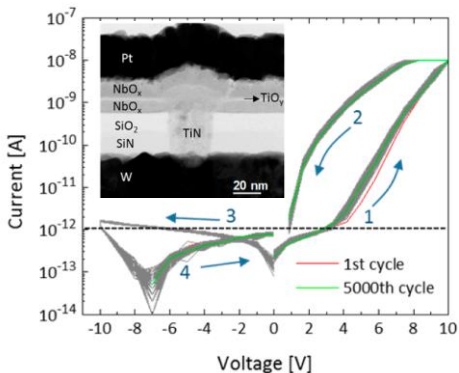
MNIST-DVS

Poker-DVS

Key component technologies we are working on

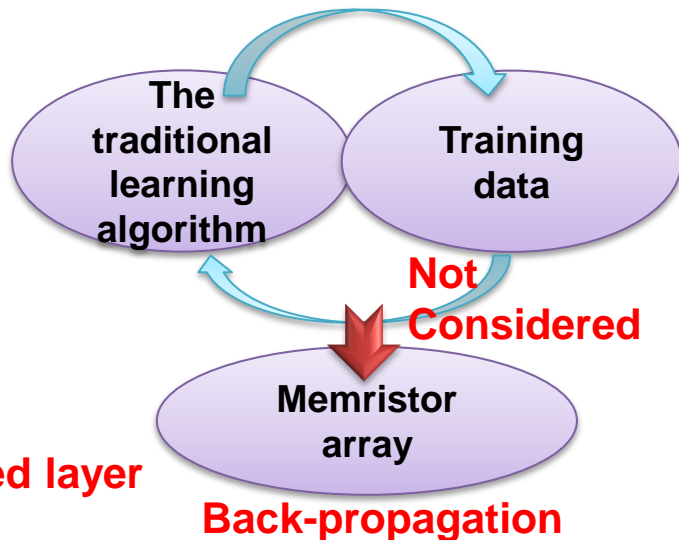
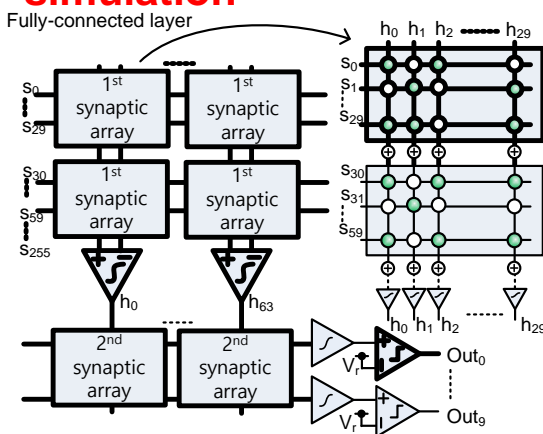
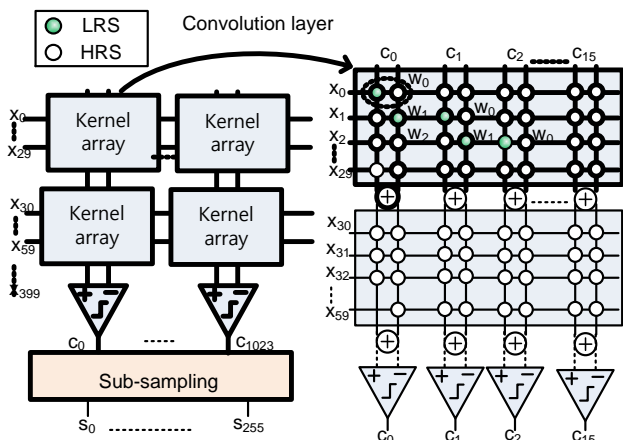
PHASE I

✓ **Material/process/device**, modeling, array characterization, circuit design, learning algorithm



Selector-free memristor array

Device modeling and memristor-CMOS hybrid circuit simulation

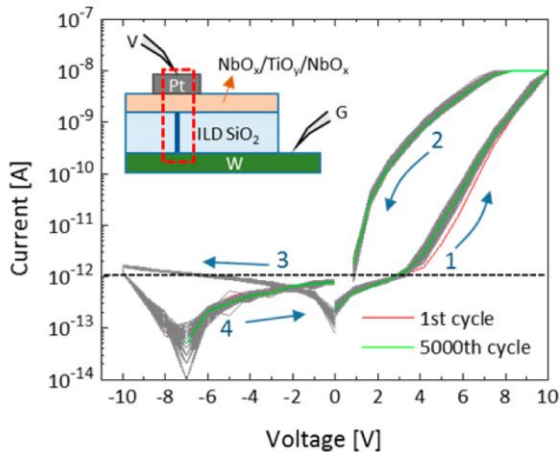


Scalable Array Architecture of Convolution/Fully-connected layer

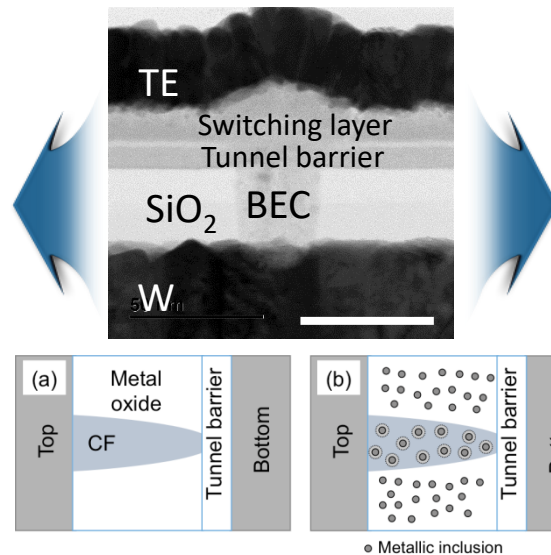
Back-propagation

Material/process/device: Self-rectifying/CMOS-compatible memristor arrays

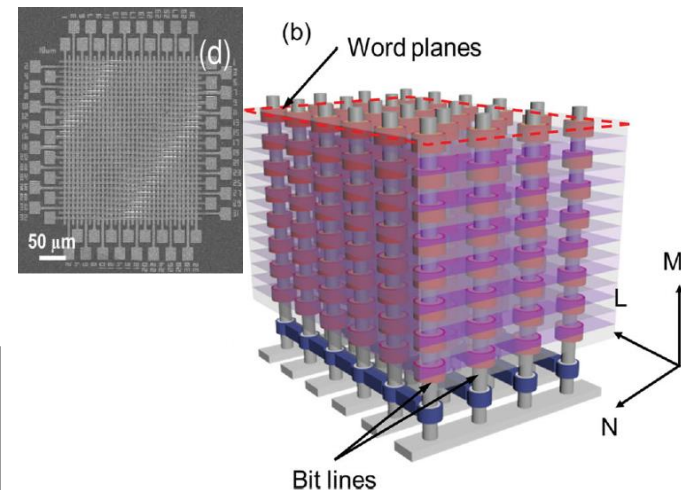
Self-rectifying behavior:
selector-free and low-power



Bio-realistic memristive materials:
CMOS-compatible process



Memristor crossbar array:
Feasibility of 3-D extension



- ✓ Innovative memristive materials **by mimicking Neurotransmitter**
- ✓ CMOS-compatible **Atomic Layer Deposition** process
- ✓ **Self-rectifying and low-power memristor** by multi-layer stacking
- ✓ 30 x 30 **CMOS-compatible TR-free vertical-type crossbar arrays**

Summary

Material/ Process/ Device

- ✓ Selector-free/self-rectifying and neurotransmitter-mimicking devices by stacking multiple layers and alloying diffusive metal
- ✓ Atomic Layer Deposition (ALD) for multiple-layer stacking

Circuit/ systems

- ✓ Scalable and expandable memristor array architecture composed of memristor-array tiles (to be used in RRAM macro)
- ✓ Basic building blocks (Memristor-CMOS hybrid)
- ✓ HW/SW platform for MCNN learning and execution
- ✓ Chip-in-the-loop learning with defect-repair scheme

Application s

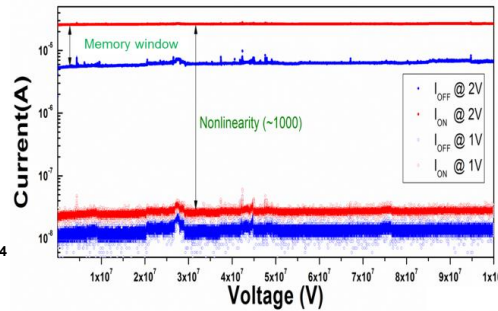
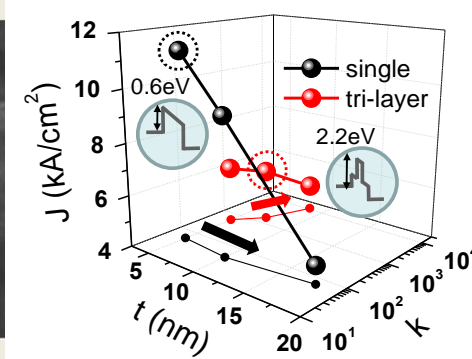
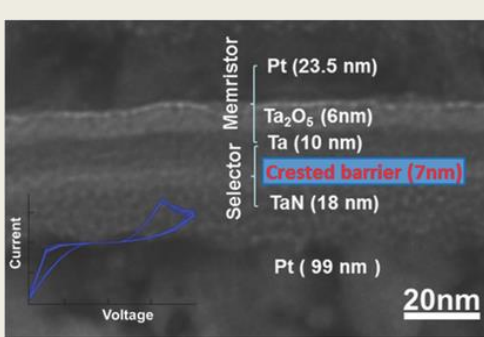
- ✓ MNIST hand-written digits (95% performance of the state-of-the-art)
- ✓ MNIST-Dynamic Vision Sensor (DVS), Poker-DVS for Event-Driven operation, ImageNet for Color Recognition, etc

Design and fabrication of memristor crossbar arrays for target applications!

Appendix: Realization of memristor in crossbar array

Multi-layer selectors and memristors ('16 Adv. Mater.)

- **Tri-layer tunnel selectors for memristor memory cells enabled by ALD**



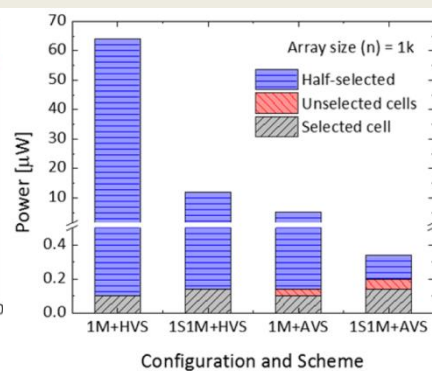
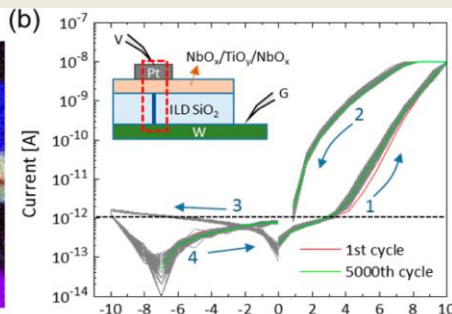
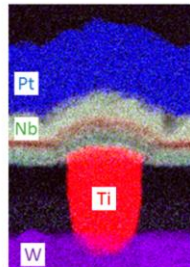
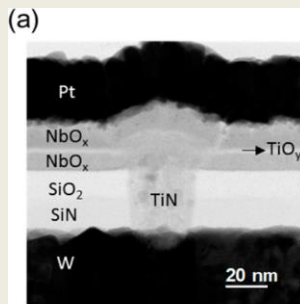
1S-1R memory

High nonlinearity (> 10³)

High endurance (> 10⁷)

Low-power and self-rectifying memristor system ('16 Nano Lett.)

- **Self-rectifying memristors and novel power-saving scheme suggested**



- ✓ Self-rectifying memristor
- ✓ Pt/NbO_x/TiO_y/NbO_x/TiN
- ✓ Low current under 10 nA
- ✓ Asymmetric voltage scheme