# Memristive Crossbar Arrays for Brain-Inspired Computing

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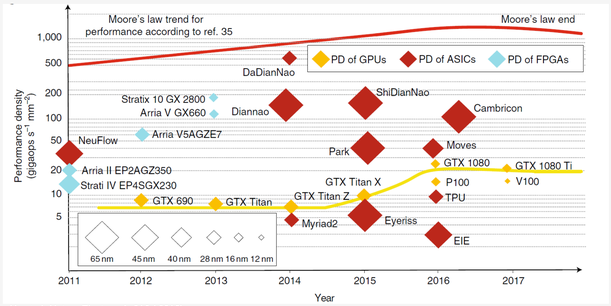
## New Materials and Devices: Young Faculty Award (YFA)

**We design, fabricate, and integrate large memristive crossbar arrays as deep neural network accelerators and spiking neural networks. This yields orders of magnitude improvements in computing speed-energy efficiency.**

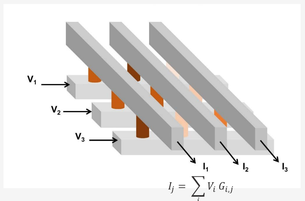
### Background

- **The problem**: Pure CMOS based AI hardware reaches a performance plateau

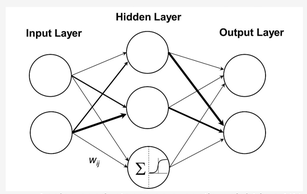



Xu et al, *Nature Electron.* 1, 216 ( 2018).

- **The solution**: In-memory analog computing and neuromorphic computing with emerging devices and arrays for much enhanced speed-energy efficiency




Xia & Yang, *Nature Materials* 18, 309 (2019).

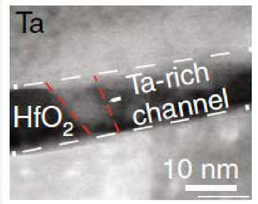


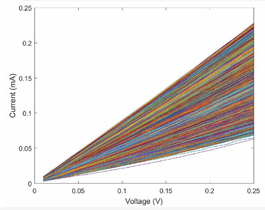

Analog conductance as synaptic weight in a NN

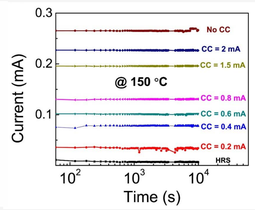
- **New challenges:** Device engineering and array integration for emerging hardware

### Building blocks: drift and diffusive memristors

- $Ta/HfO_2$ device offers **multilevel (>64) & stable resistance states, analog resistance tuning, high endurance (120 billion cycles), fast speed, & IV linearity**
- Demonstrated 2 nm scalability, 8 layer stackability, and CMOS compatibility

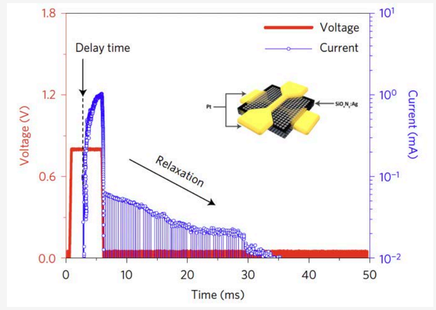


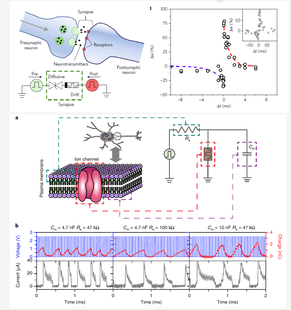




*Scientific Reports* 6, 28525 (2016). US patent: 10186660.

- Diffusive memristor offers diffusive dynamics (relaxation & delay) that enable **faithful emulation of biological synapses and neurons**
- 1 diffusive memristor + 1 drift memristor = 1 synapse; 1 diffusive memristor = 1 neuron



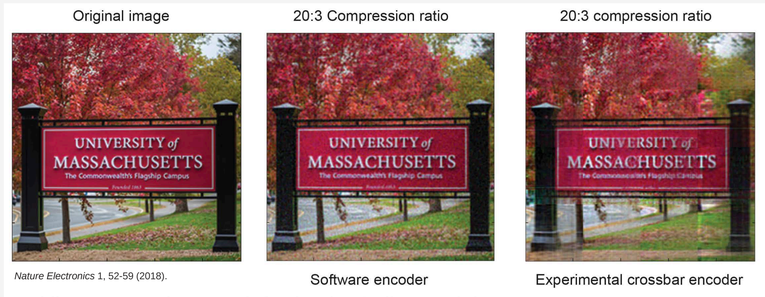

*Nature Materials* 16, 101-108 (2017).




*Nature Electronics* 1,137-145 (2018).

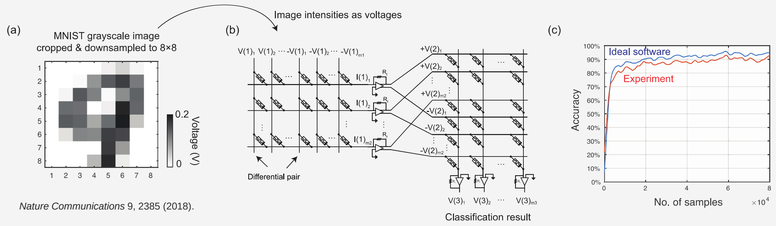
### Analog computing & machine learning demonstrations

- Image Compression with a 128x64 1T1R array



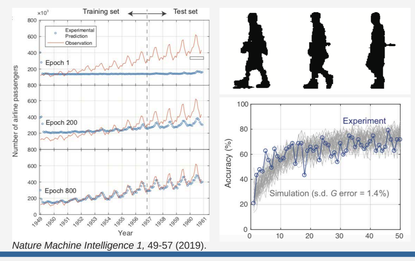

*Nature Electronics* 1, 52-59 (2018).

- Multilayer Neural Network for *in-situ* Online Training



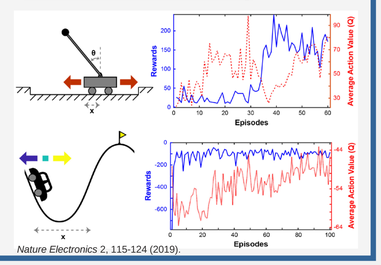

*Nature Communications* 9, 2385 (2018).

- Long Short-Term Memory (LSTM)




*Nature Machine Intelligence* 1, 49-57 (2019).

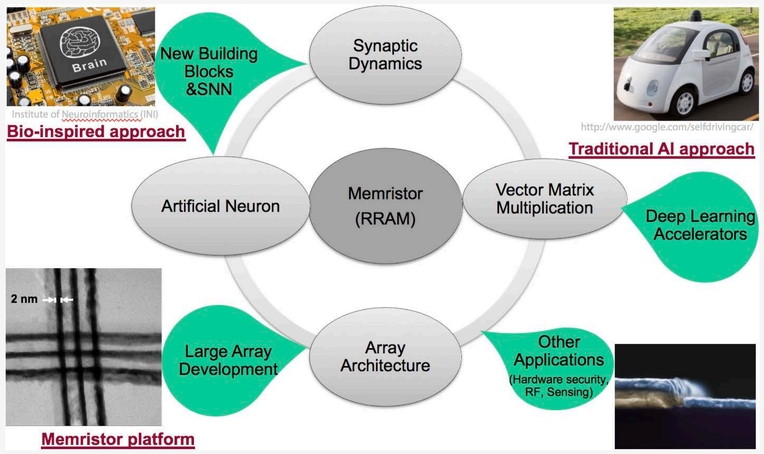
- Reinforcement Learning




*Nature Electronics* 2, 115-124 (2019).

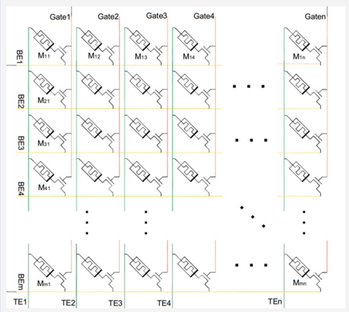
### Overview of our program

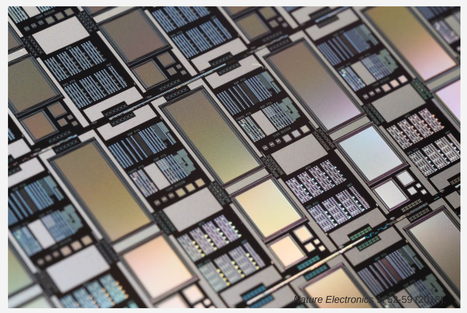
- Experiments working on materials/devices, fabrication/integration and circuits/systems
- Main focus is emerging hardware for machine intelligence and neuromorphic computing
- Exploring new frontiers in hardware security, 5G and sensing




### Largest analog memristor crossbar array to accelerate deep learning

- 1T1R architecture enables **precise conductance tuning**, **linear and symmetric weight updating**, **reduces variability and avoids sneak path problem**
- **One step in-memory vector matrix multiplication** through Ohm's law and Kirchhoff's current law, leading to high throughput and energy efficiency
- High yield (99.8%) post processing by integrating $Ta/HfO_2$ memristors with foundry made transistor arrays
- Potential to interface with analog signal to further increase energy efficiency

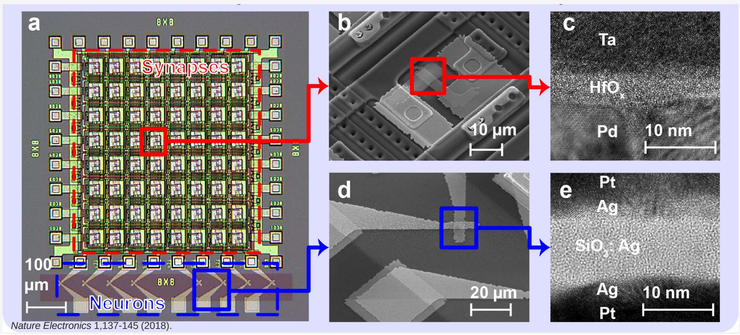


*Nature Electronics* 1, 52-59 (2018).

### Fully memristive neural network

- $Ta/HfO_2$ drift memristors as synapses, Ag:SiOx drift memristors as neurons
- Unsupervised learning enabled by interaction between the synapses and neurons




*Nature Electronics* 1,137-145 (2018).

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