Ferroelectric Synapse

Yuewei Yin

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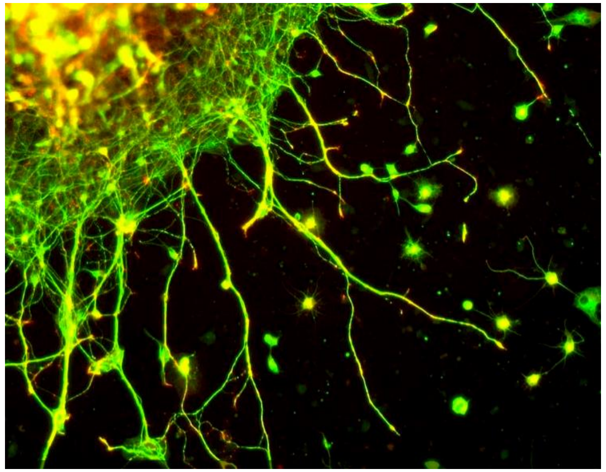
Prof. Xu's group meeting

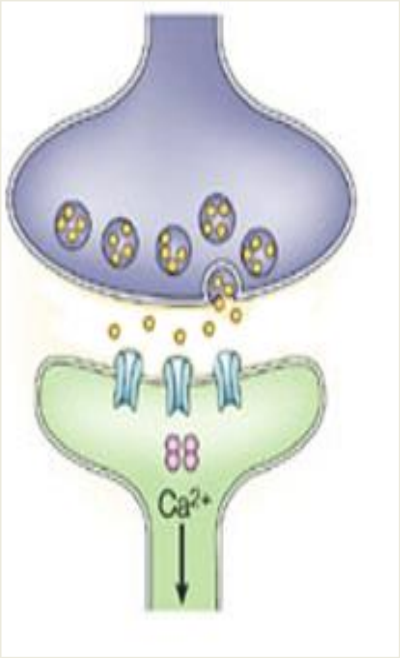
How Does the Brain Differ From a Modern-Day Computer?

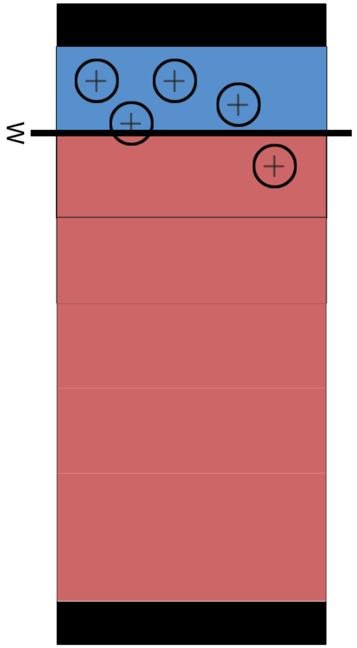


- Slow
- Parallel Processing
- High degree of interconnectivity
- Spiking Neural Nets
- Ionic
- Analogue

Synapse vs. memristor

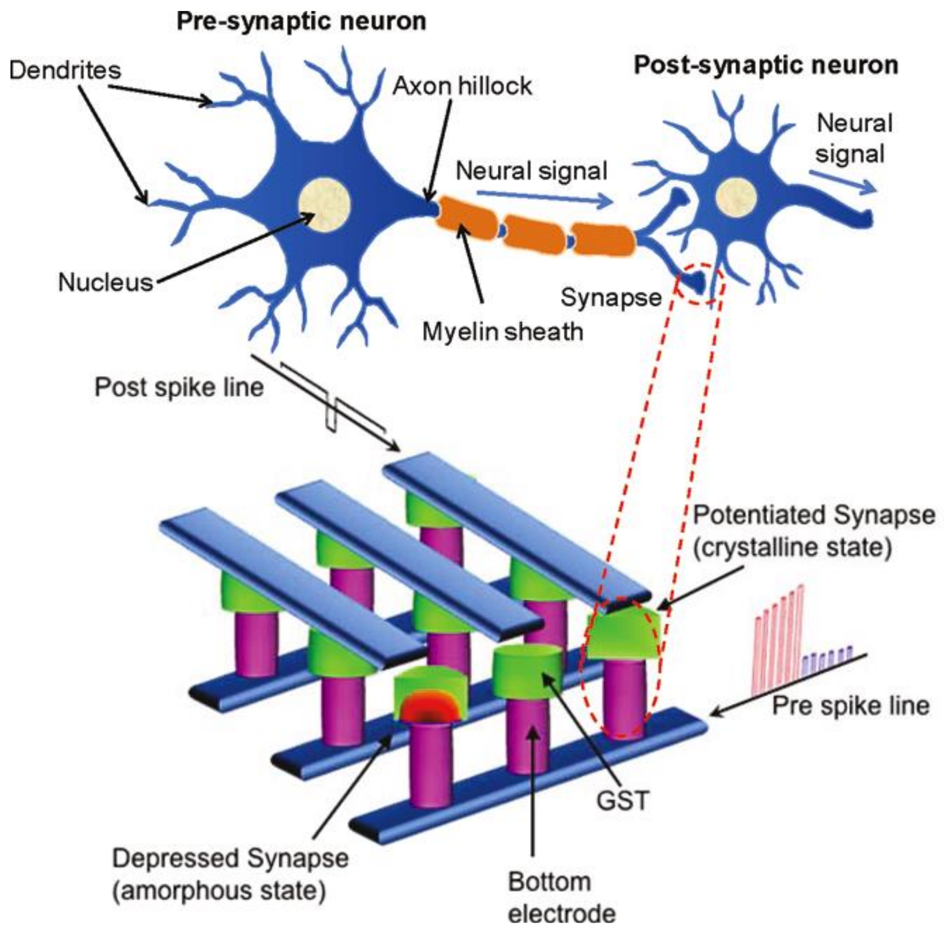
- The human brain consists of ~10^{11} neurons and an extremely large number of synapses, ~10^{15}, which act as a highly complex interconnection scheme among neurons. Synapses dominate the architecture of the brain and are responsible for massive parallelism, structural plasticity, and robustness of the brain. They are also crucial to biological computations that underlie perception and learning.
- As compared to biological systems, today's programmable computers are 6 to 9 orders of magnitude less efficient in complex environments. Simulating 5 seconds of brain activity takes 500 s and needs 1.4MW of power, when state-of-the-art supercomputers are used. The power dissipation in the human central nervous system is on the order of 10W. The superior features of the brain, lacking in today's computational systems, are ultrahigh density, low energy consumption, parallelism, robustness, plasticity, and fault-tolerant operation.

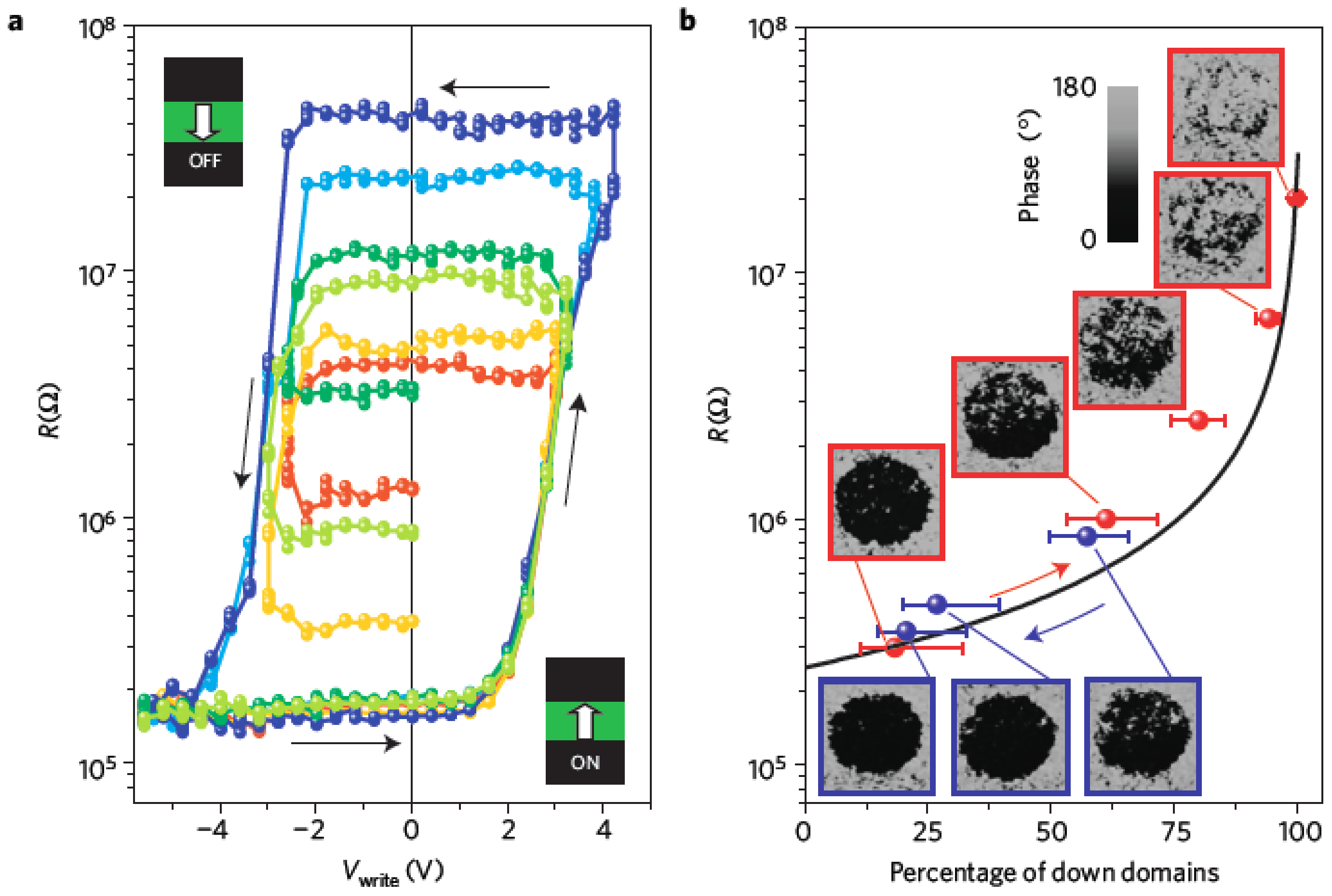




In the brain, learning is achieved through the ability of synapses to reconfigure the strength by which they connect neurons (synaptic plasticity). In promising solid-state synapses called memristors, conductance can be finely tuned by voltage pulses.

Ferroelectric memristor





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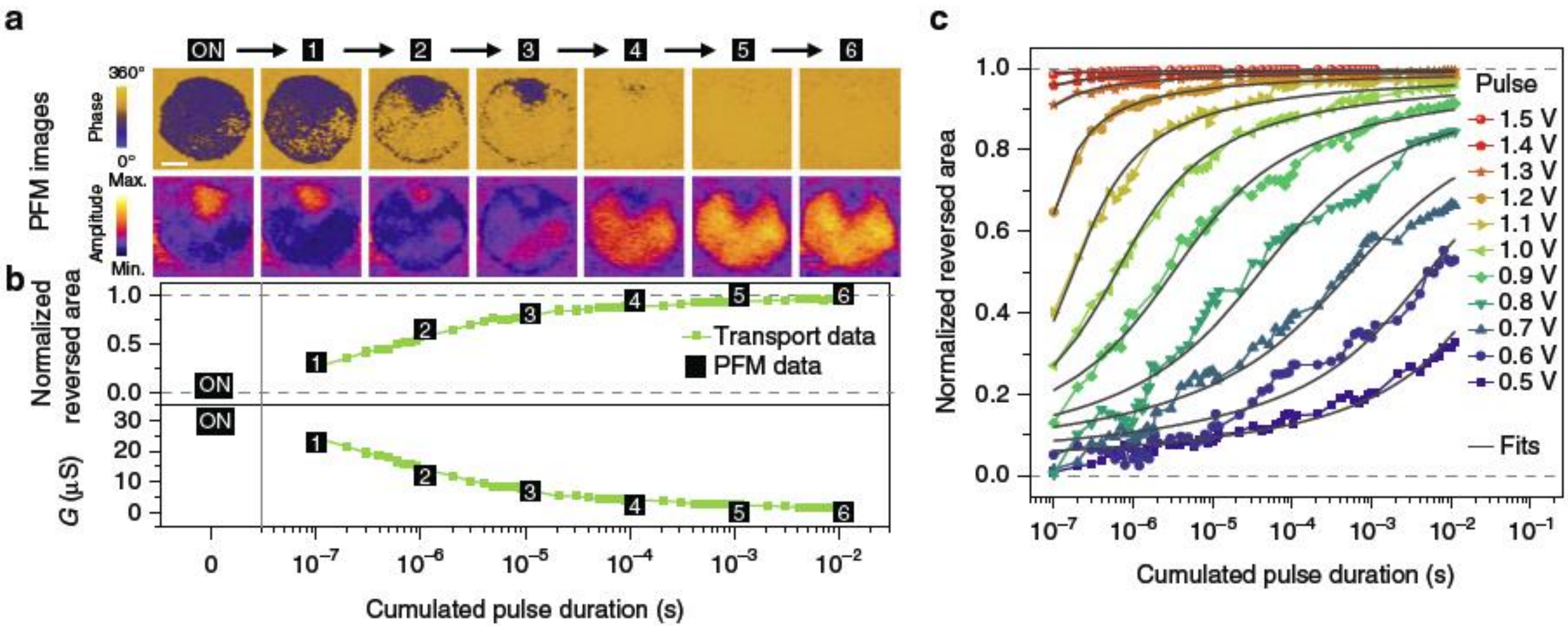
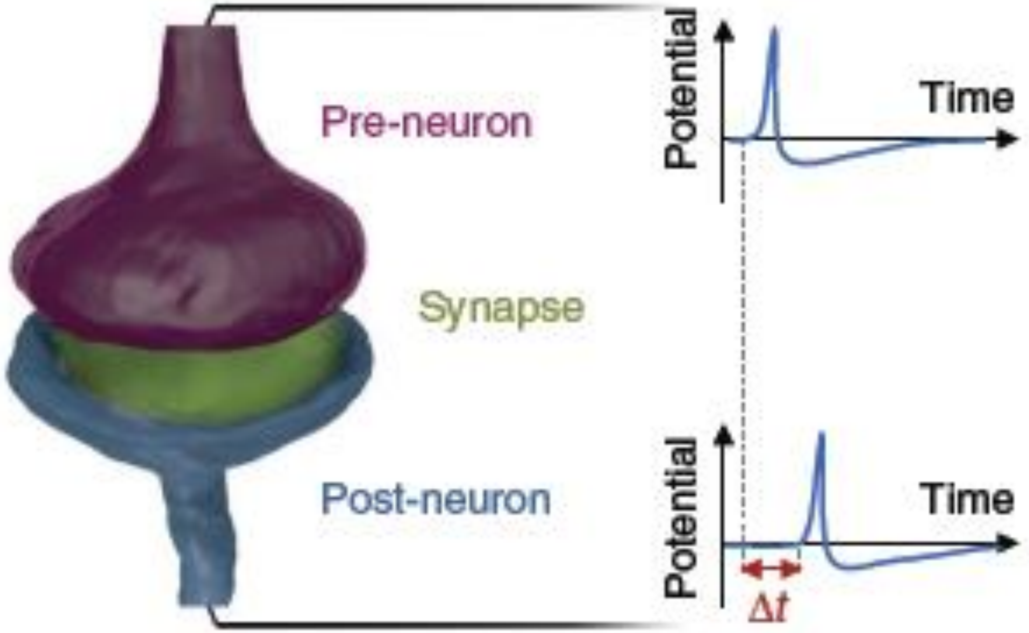
Ferroelectric domain dynamics



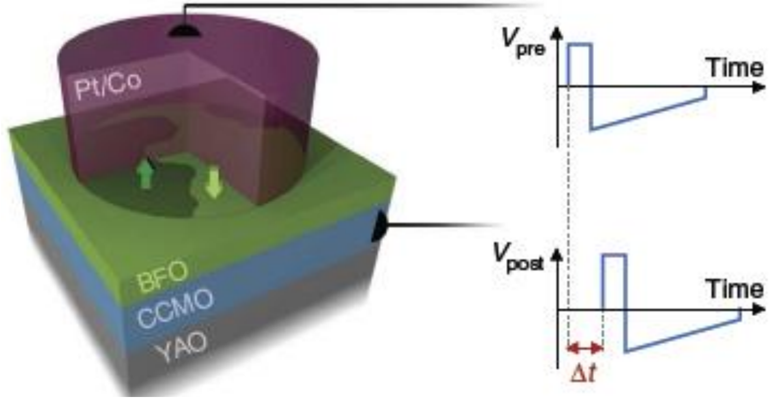
- The evolution of the phase images in PFM reveals the gradual reversal of the polarization from up (dark domains) to down (bright domains).

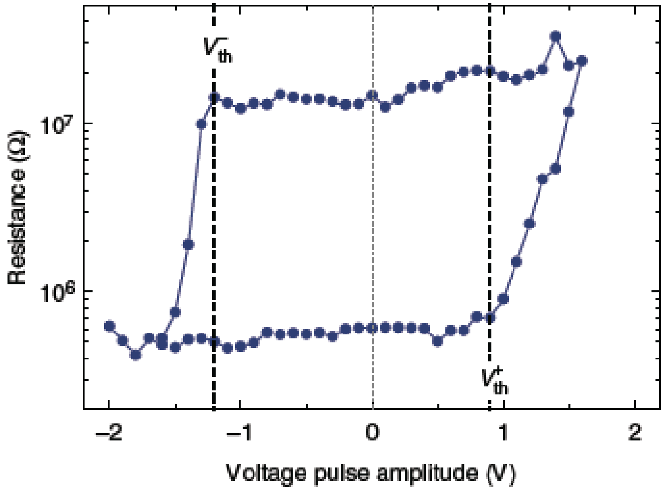
Spike timing-dependent plasticity

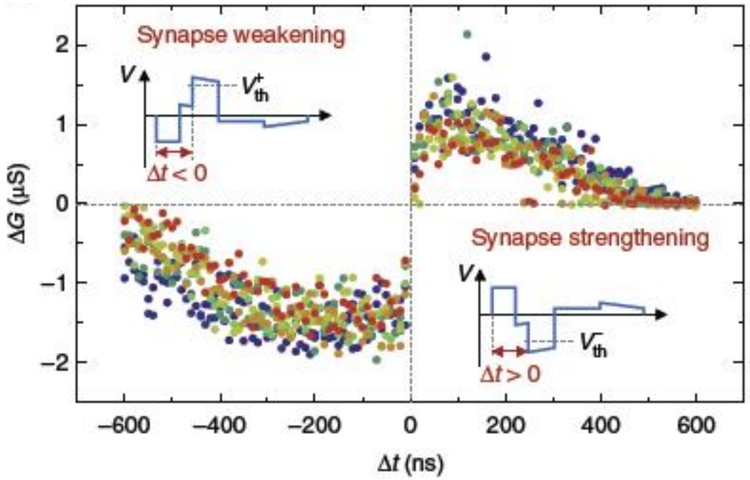
- Cortical information flows from neuron to neuron through synapses of variable connection strength. The overall distribution of the synaptic strengths provides the neural network with memory, while learning is achieved through the synapses' reconfiguration (that is, plasticity). Several mechanisms regulating the evolution of the synaptic strengths have been proposed. A particularly promising one is spike timing-dependent plasticity (STDP) through which the synaptic strengths evolve depending on the timing and causality of electrical signals from neighboring neurons. The implementation of STDP in artificial neural networks thus emerges as a crucial milestone towards the realization of self adaptive electronic architectures.



STDP in ferroelectric memristor







- When both pre- and post-neuron spikes reach the memristor with a delay, their superposition produces a combined waveforms. The resulting combined waveform transitorily exceeds the threshold voltage, leading to an increase (synapse strengthening) or a decrease (synapse weakening) of the FTJ conductance, depending on the sign of delay time. Only closely timed spikes produce a conductance change whereas long delays leave the device unchanged.

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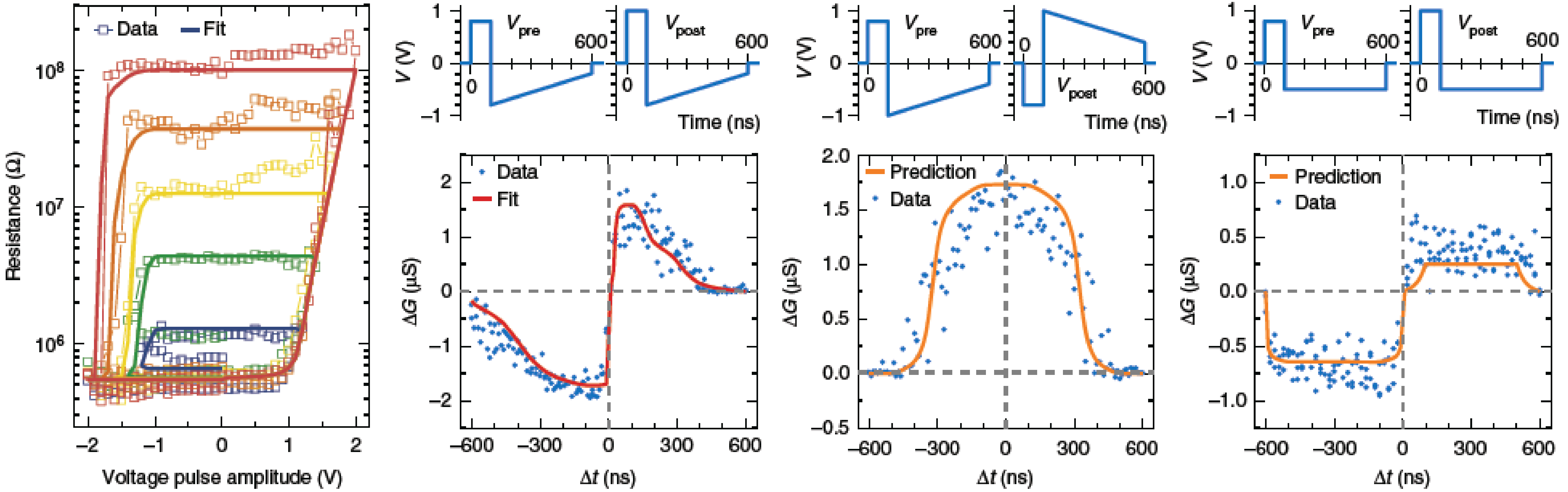
STDP in ferroelectric memristor



- Examples of STDP learning curves of different shapes. For each device, simultaneous fits of data in pre- and post-synaptic spikes (solid lines) allow the prediction of new learning curves in conductance variations (orange lines).

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