Ferroelectric Neuromorphic Devices

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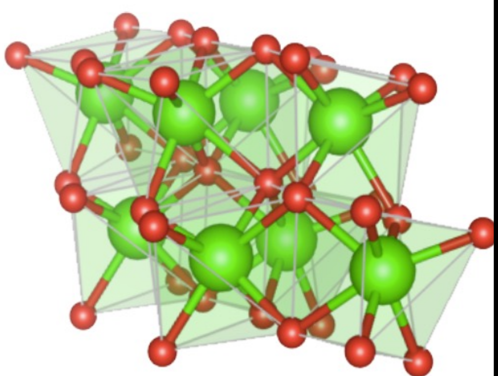
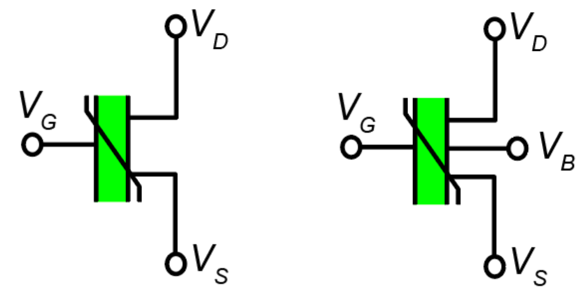
Neuromorphic Ferroelectric FET

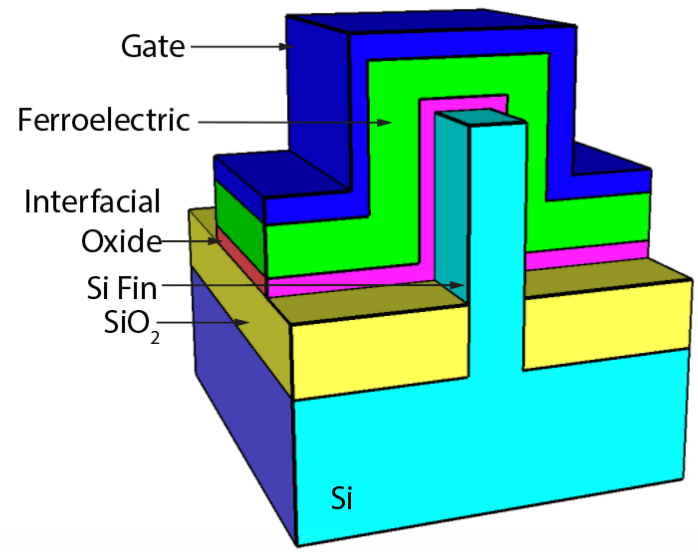
Ferroelectric Oxide
Neuromorphic Properties



Ferroelectric FET

- Hysteresis
- Gain
- Plasticity
- Polymorphism
- Stochasticity
- Circuit Configurability



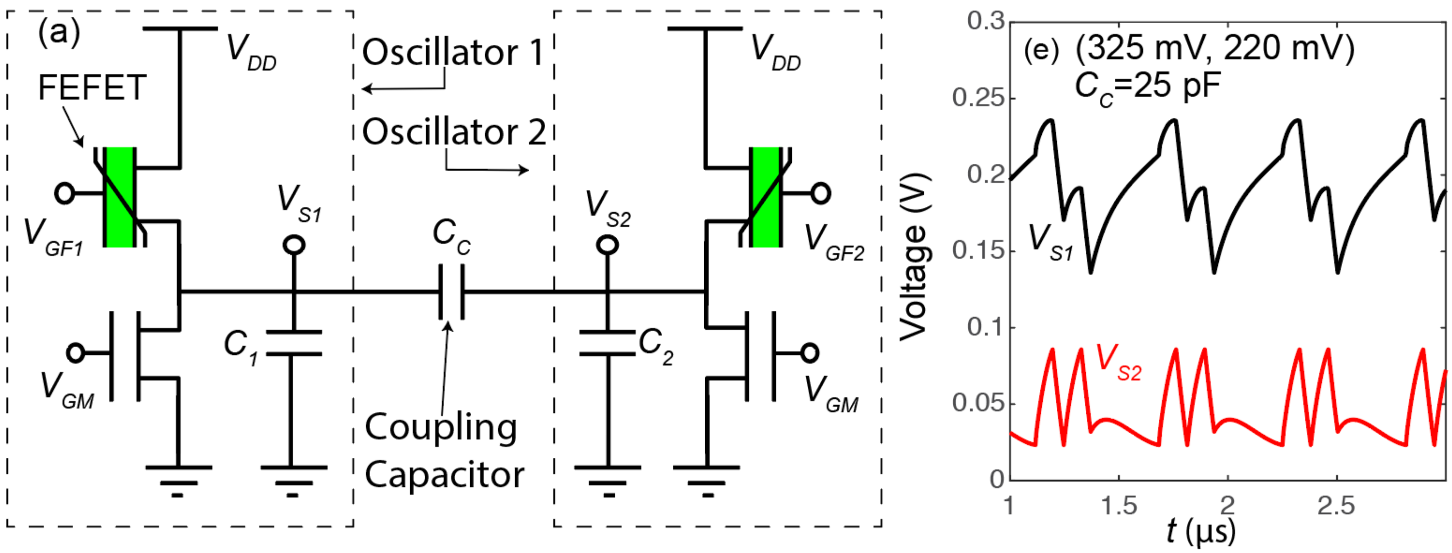


A Ferroelectric FET is the only neuromorphic device with an intrinsic gain!

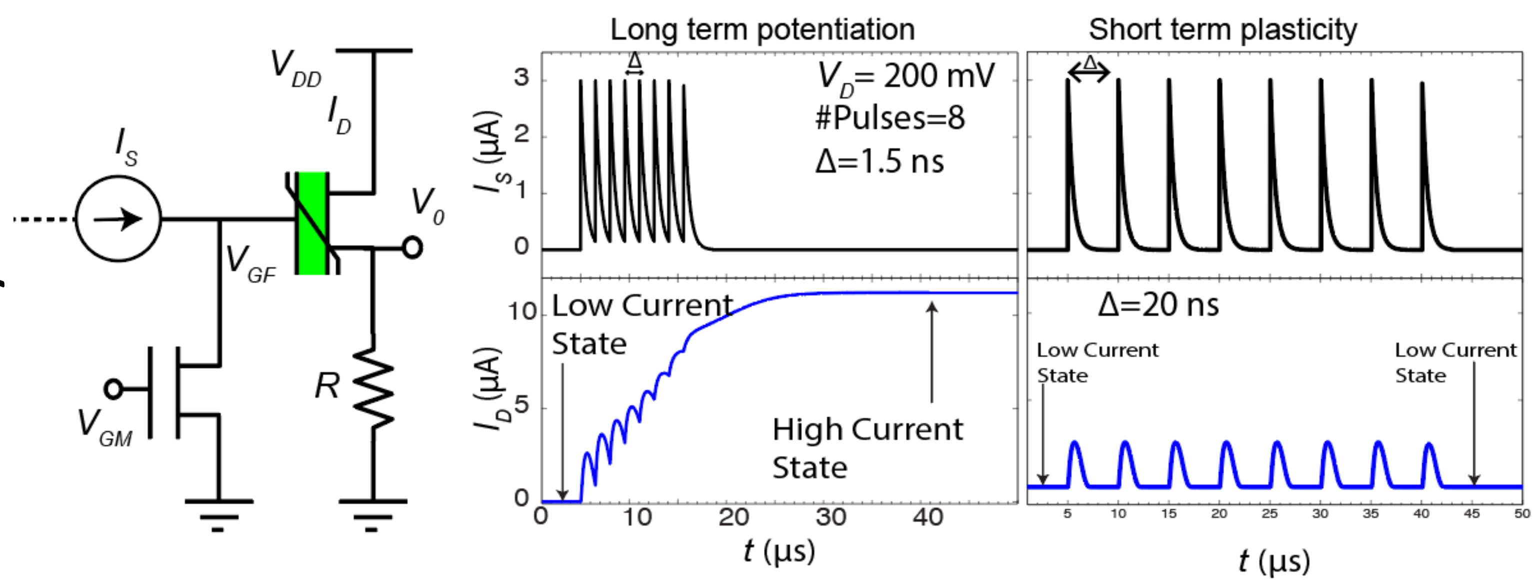
Neuromorphic Ferroelectric Circuits

Same ferroelectric FET leads to different neuro-synaptic functions in different circuit configurations.

Neuro-dynamical System

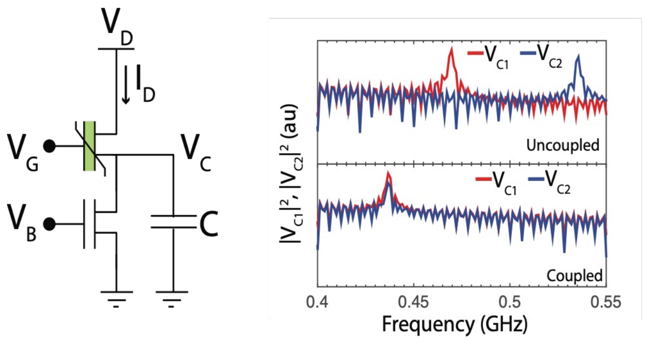


Synaptic System

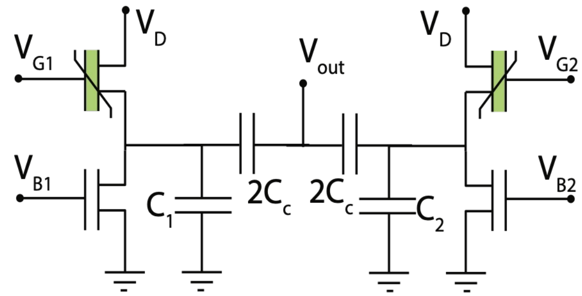


Family of Neuromorphic FEFET Circuits

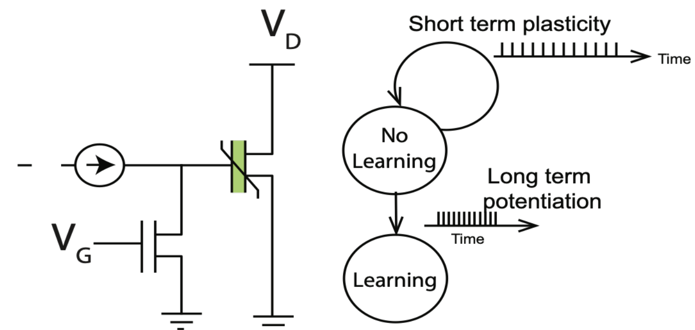
Relaxation Oscillator



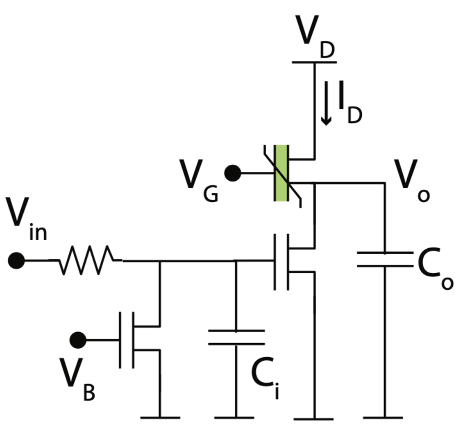
Coupled Dynamical Oscillator



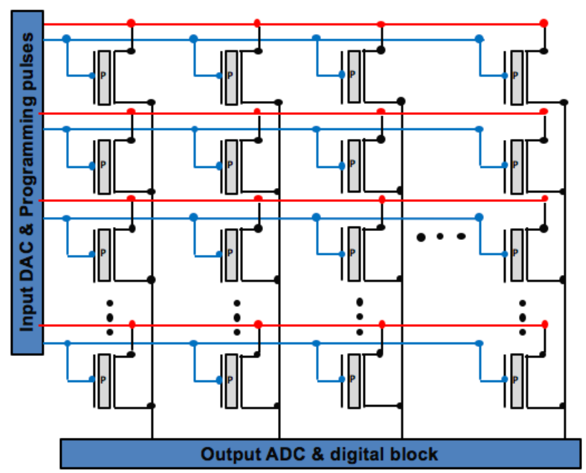
Synaptic Learning



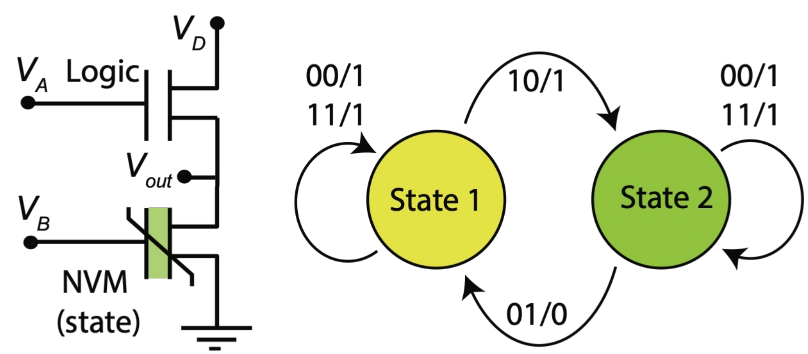
IF Neuron



Vector Matrix Multiplier

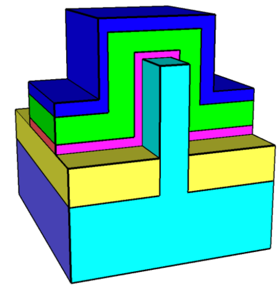


Nonvolatile Finite State Machines

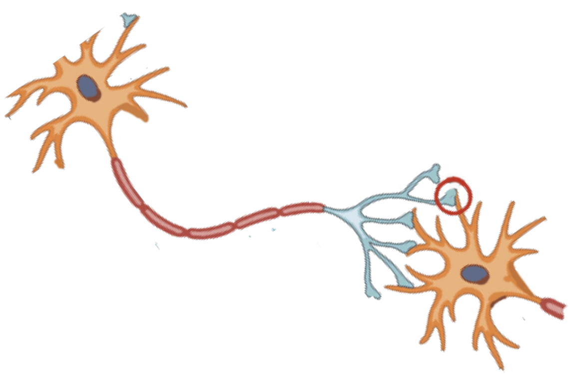


Neuromorphic Ferroelectric FET

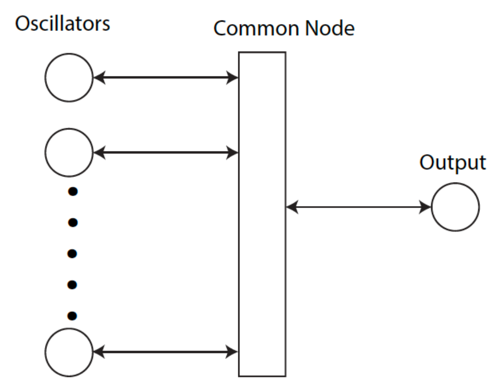
Ferroelectric Devices



Activity Dependent Synaptic Plasticity

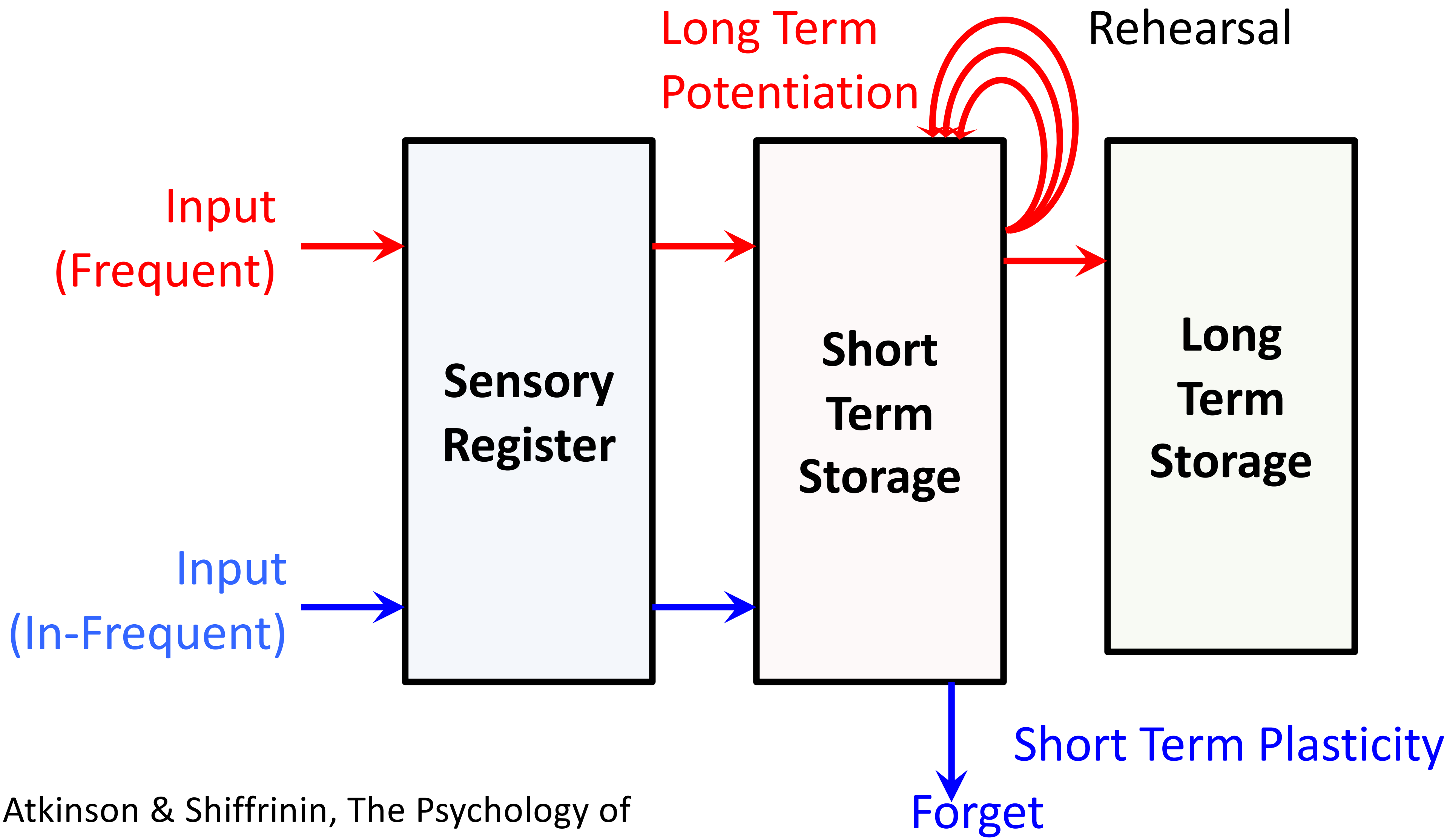


Coupled oscillator Networks



Memory, Learning and Neuroscience

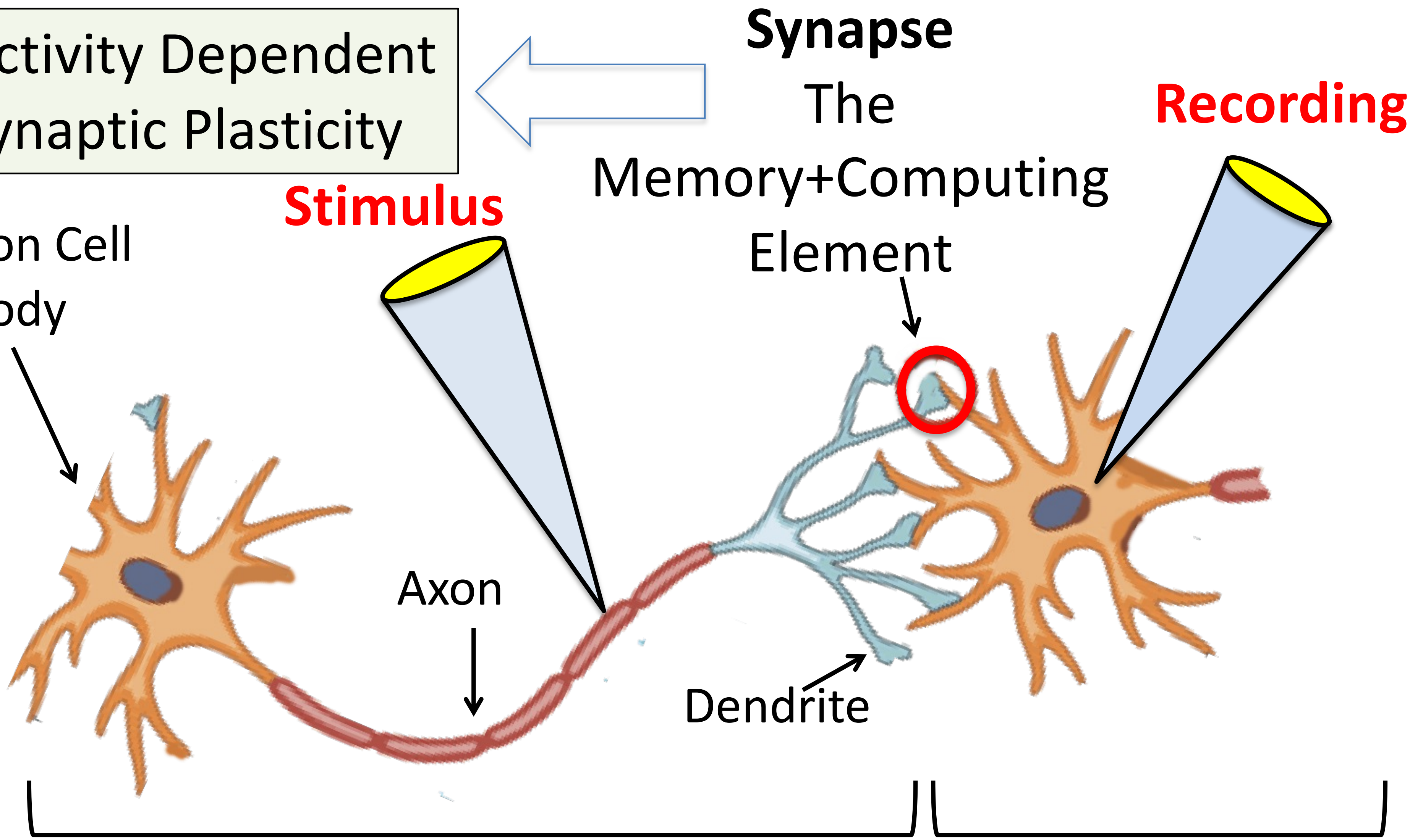
Multistore model of Memory and Learning



Atkinson & Shiffrinin, The Psychology of Learning and Motivation: Advances in Research and Theory (1968)

Neurophysiological Basis of Learning

Activity Dependent Synaptic Plasticity



Schaffer Collateral, Mossy Fiber, Perforant Fiber Pathways In Hippocampus

Bliss et al., J. Physiology 232, 331 (1973).

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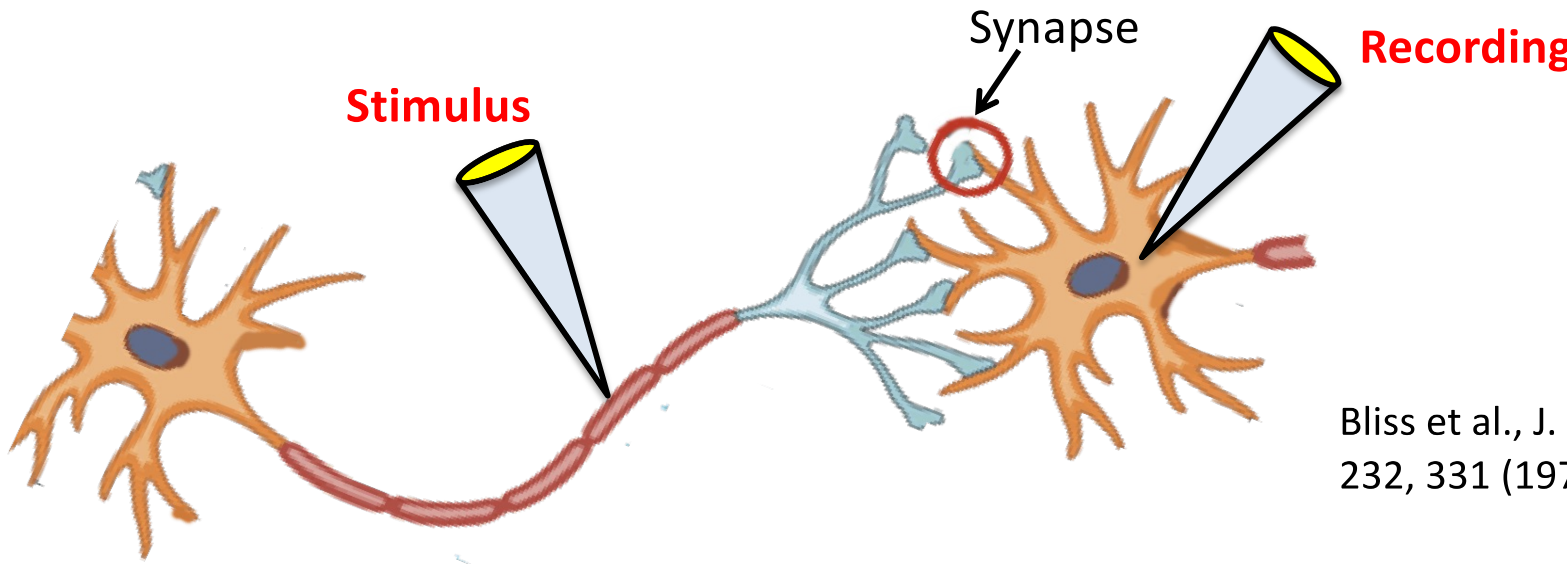
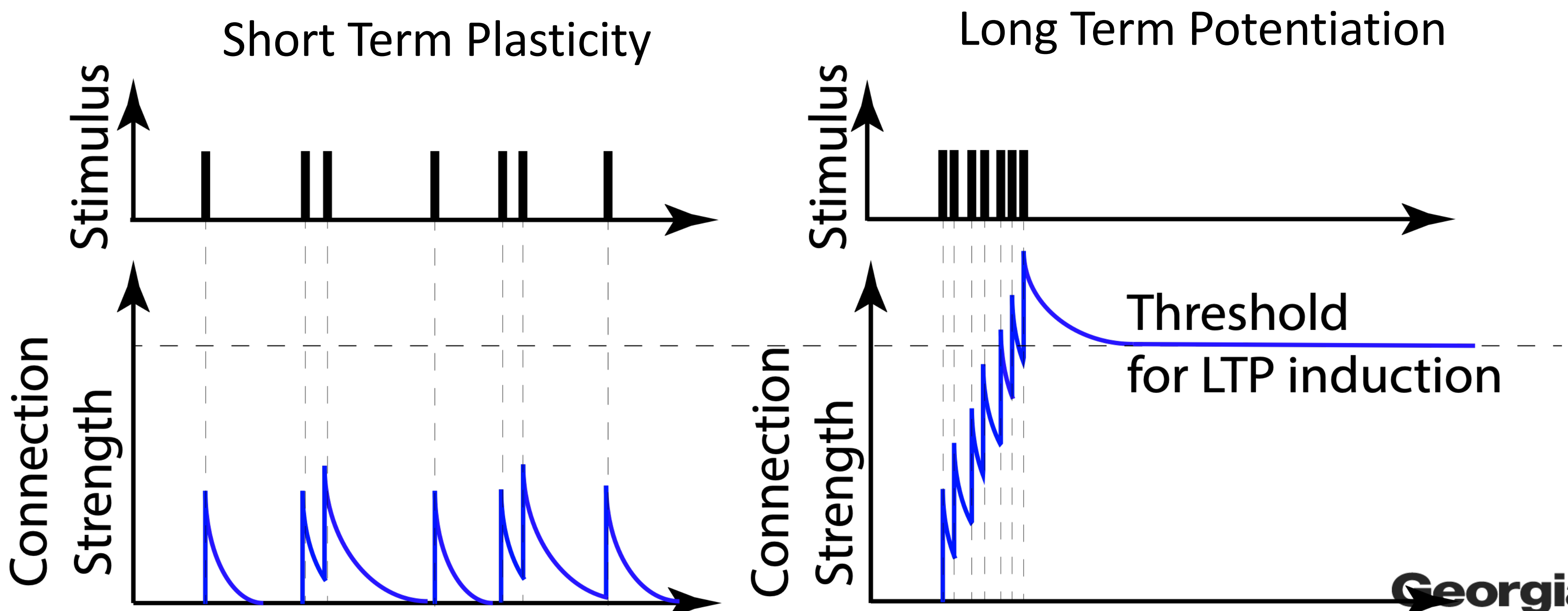
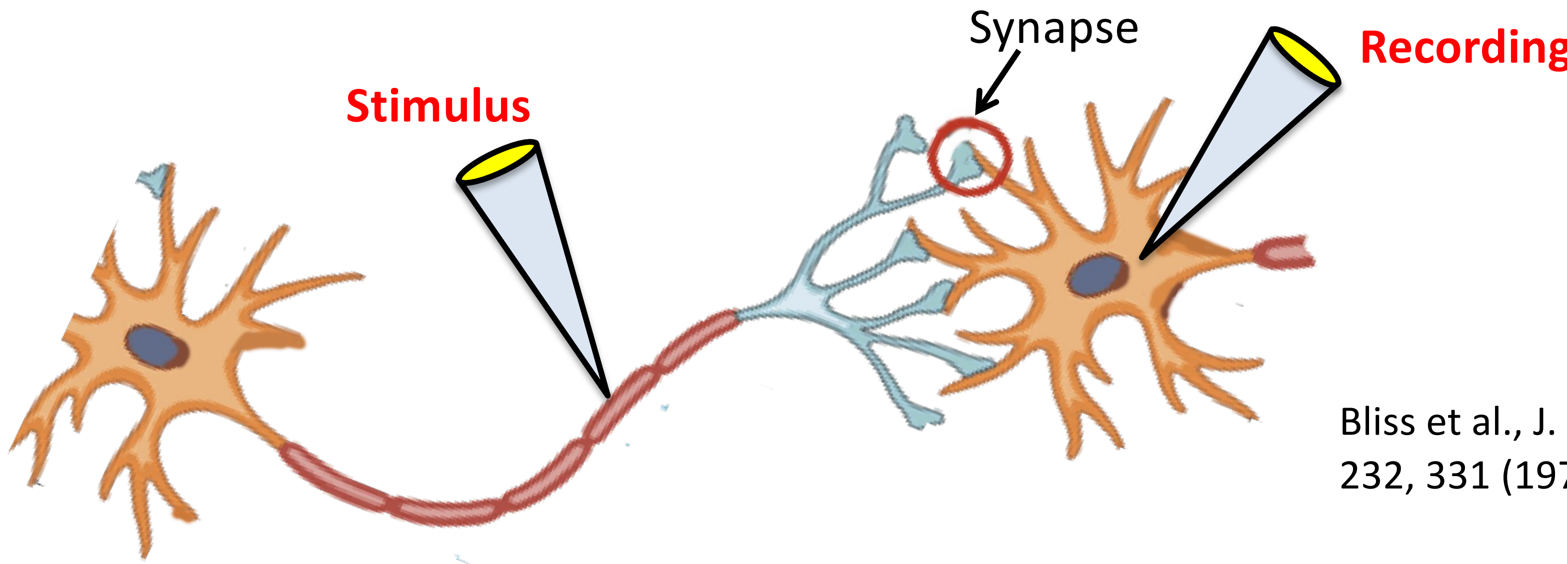
Neurophysiological Basis of Learning



Bliss et al., J. Physiology 232, 331 (1973).

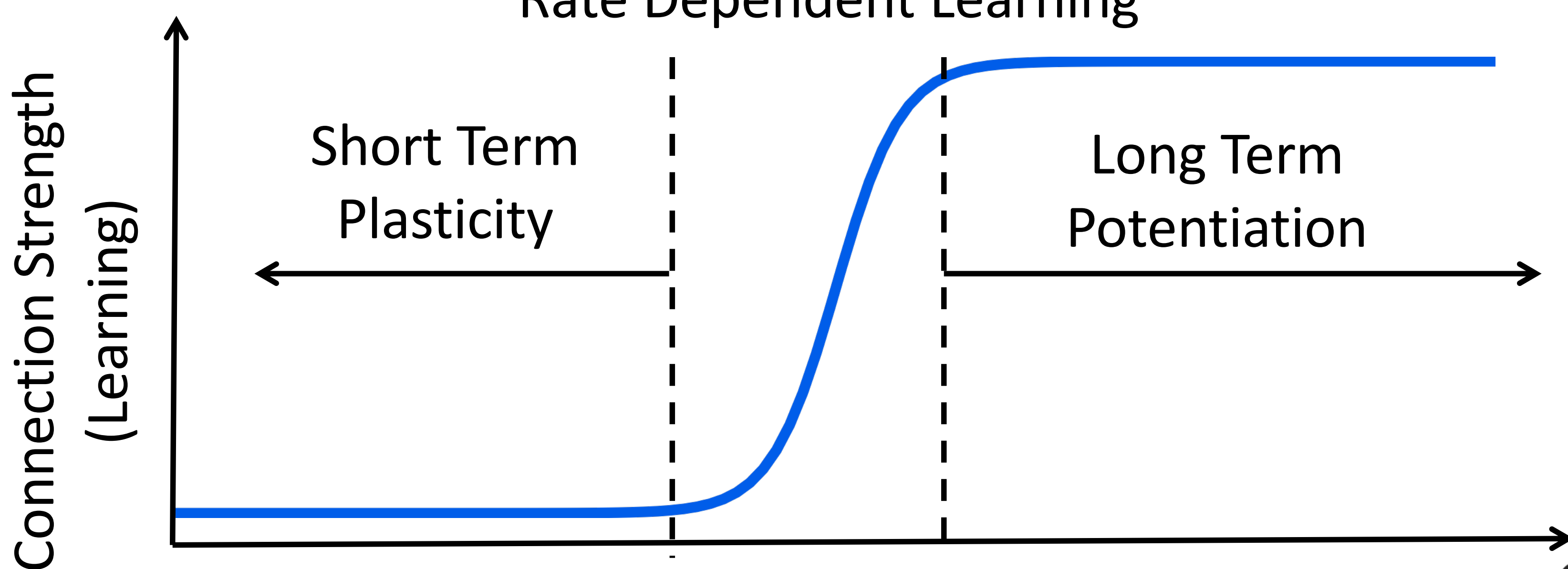


Neurophysiological Basis of Learning

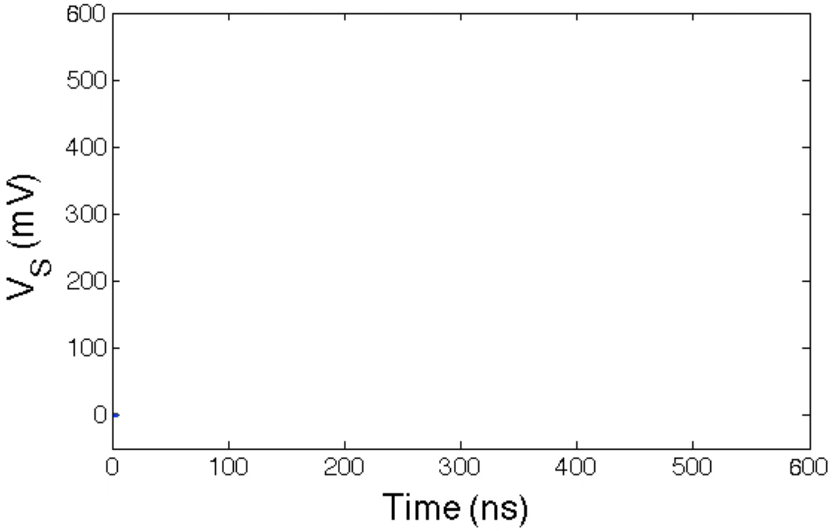


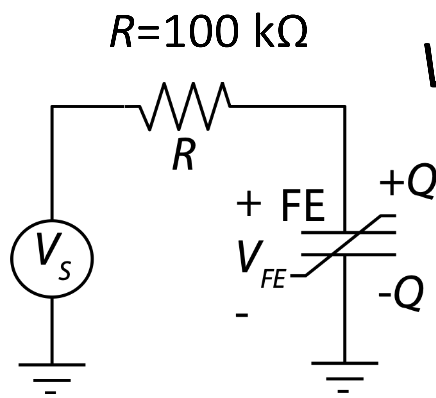
Bliss et al., J. Physiology 232, 331 (1973).

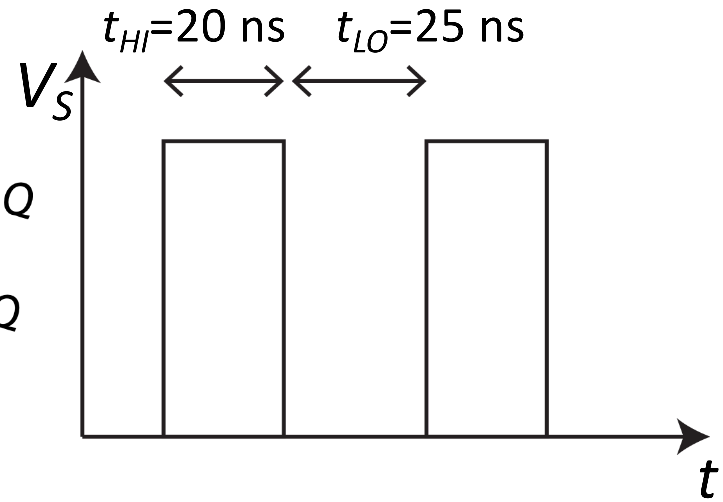
Activity dependent Synaptic Plasticity & Rate Dependent Learning

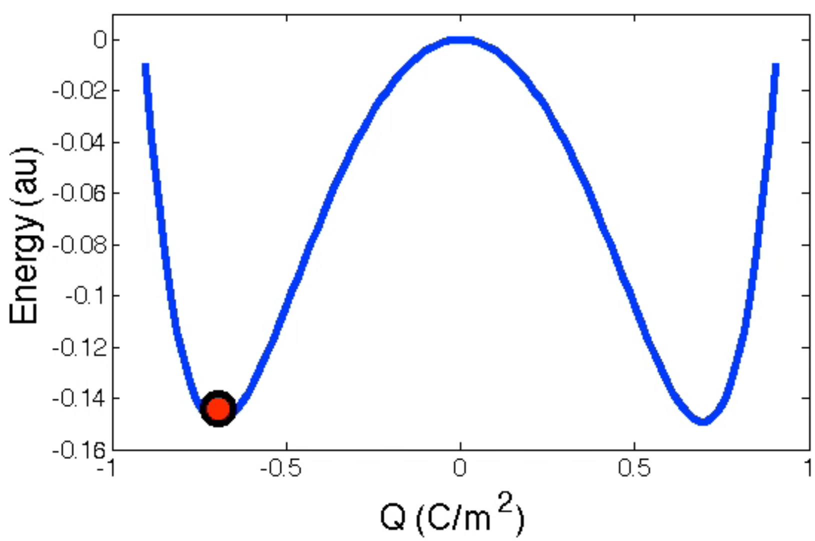


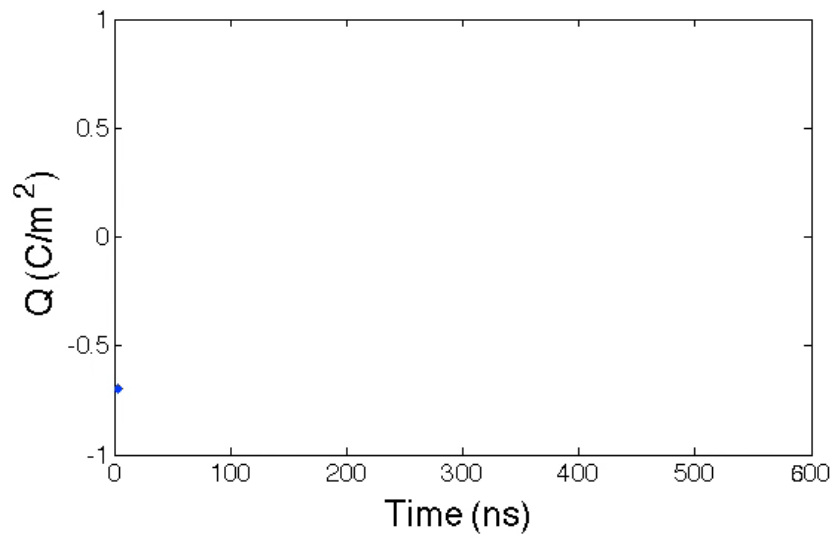
Short Term Plasticity: Simulation





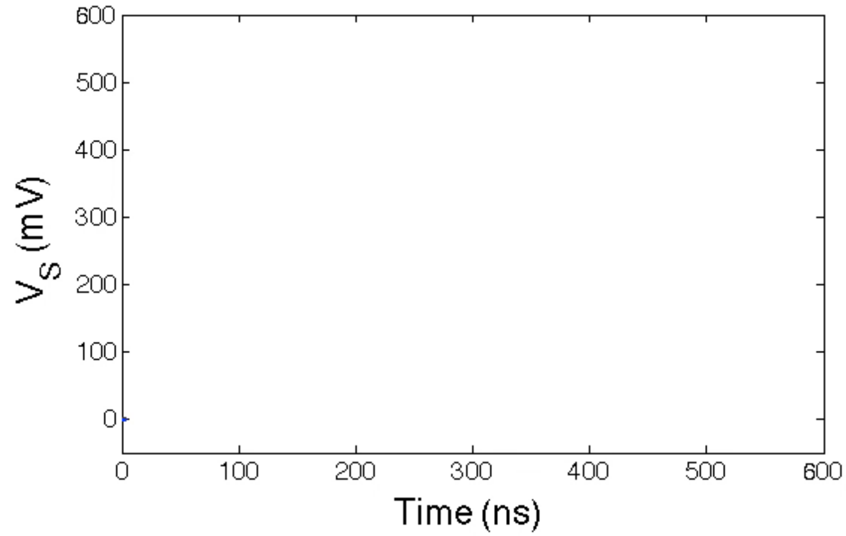


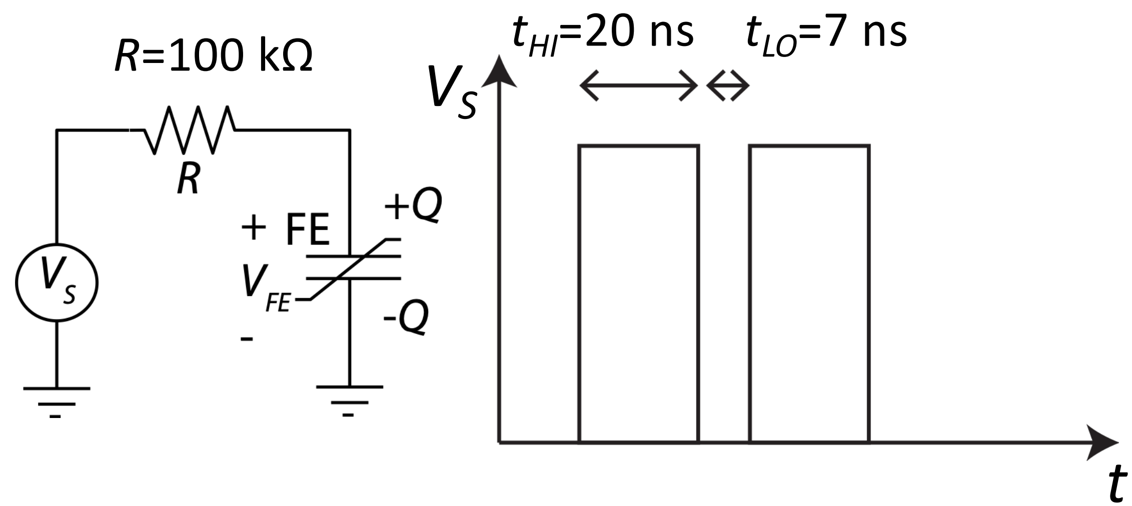


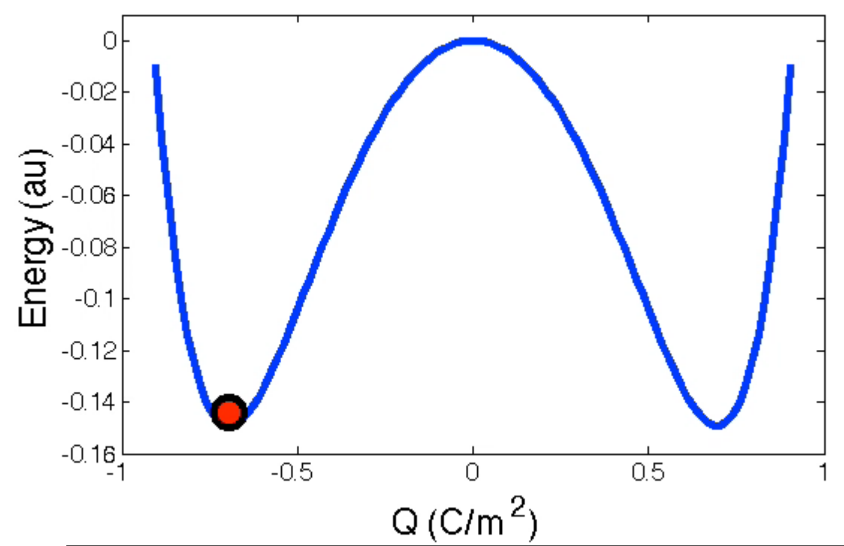


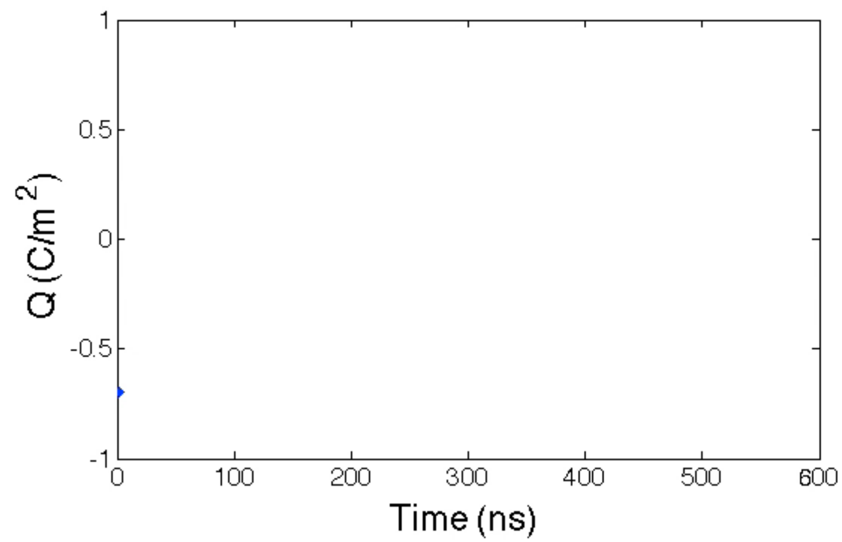
In-frequent rehearsal does not lead to ferroelectric switching (no learning)!

Long Term Potentiation: Simulation



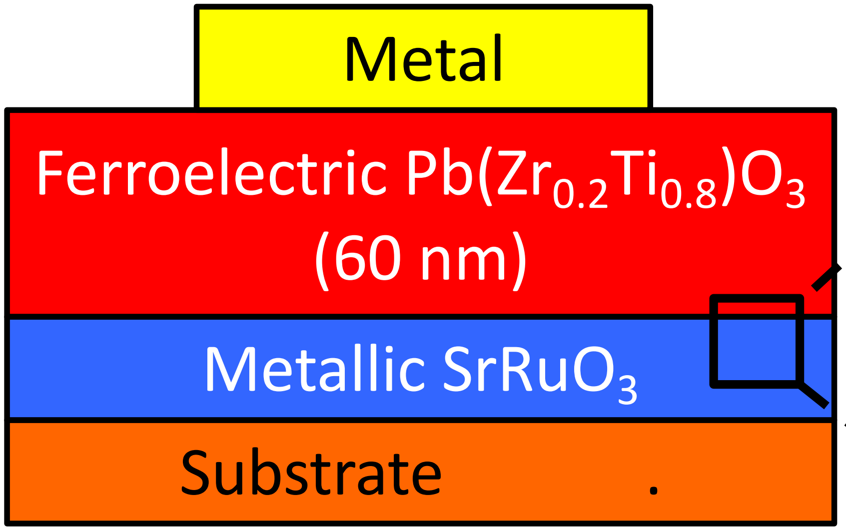




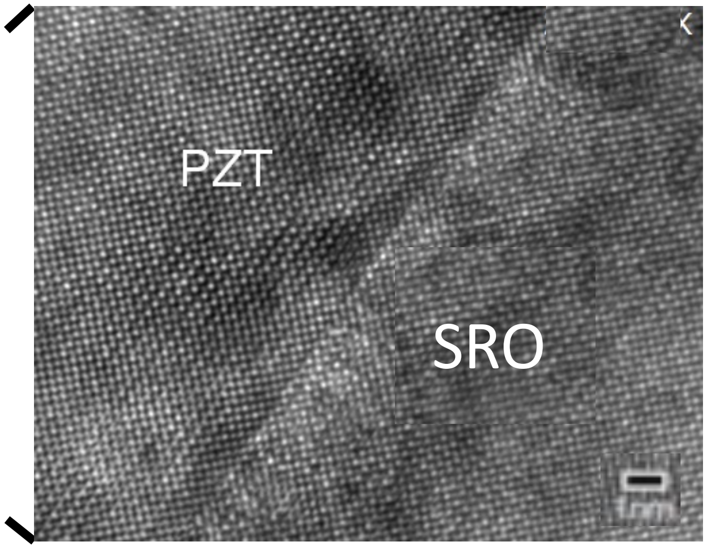


Frequent rehearsal does not lead to ferroelectric switching (learning)!

Characterization of Ferroelectric Film

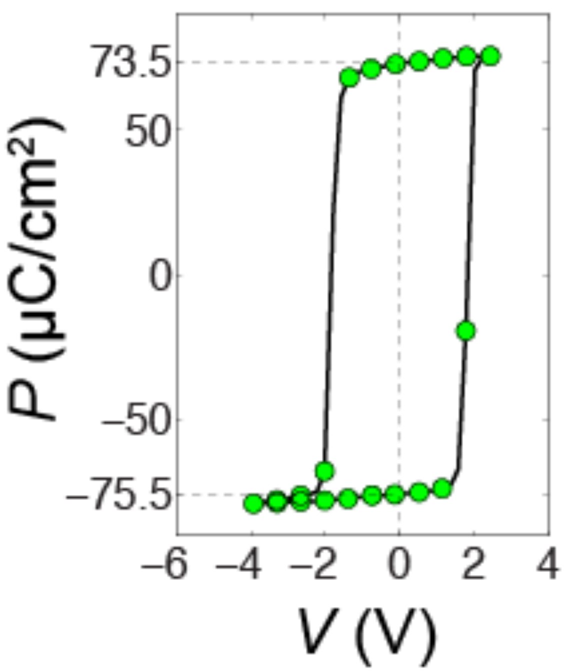


TEM Cross-section

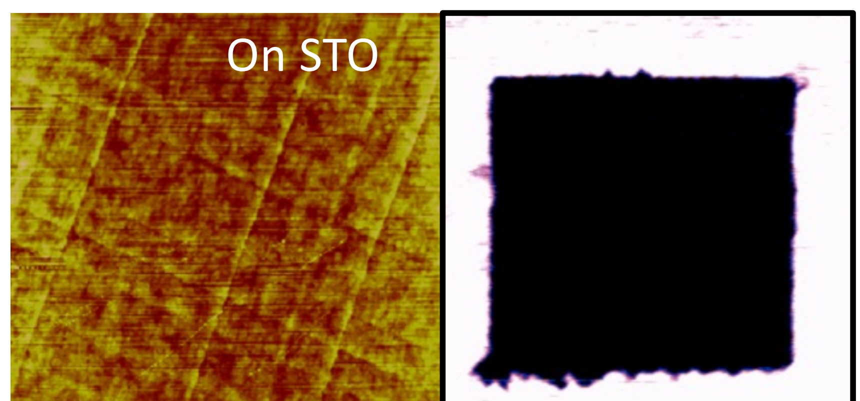


Courtesy: Pan group, U. Mich.

Ferroelectric Hysteresis

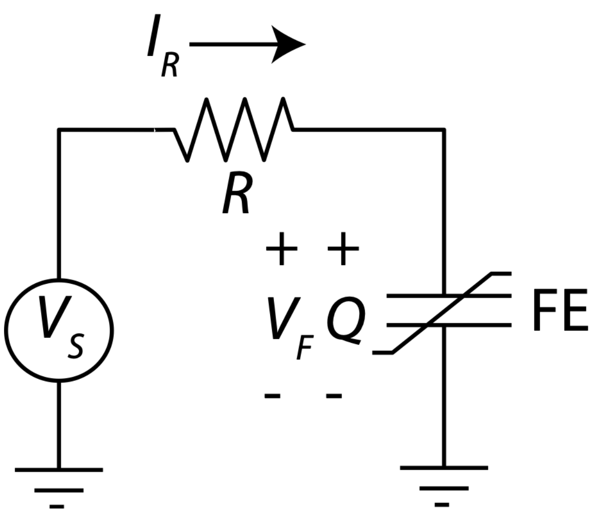


Surface Topography
and Piezo-Respose

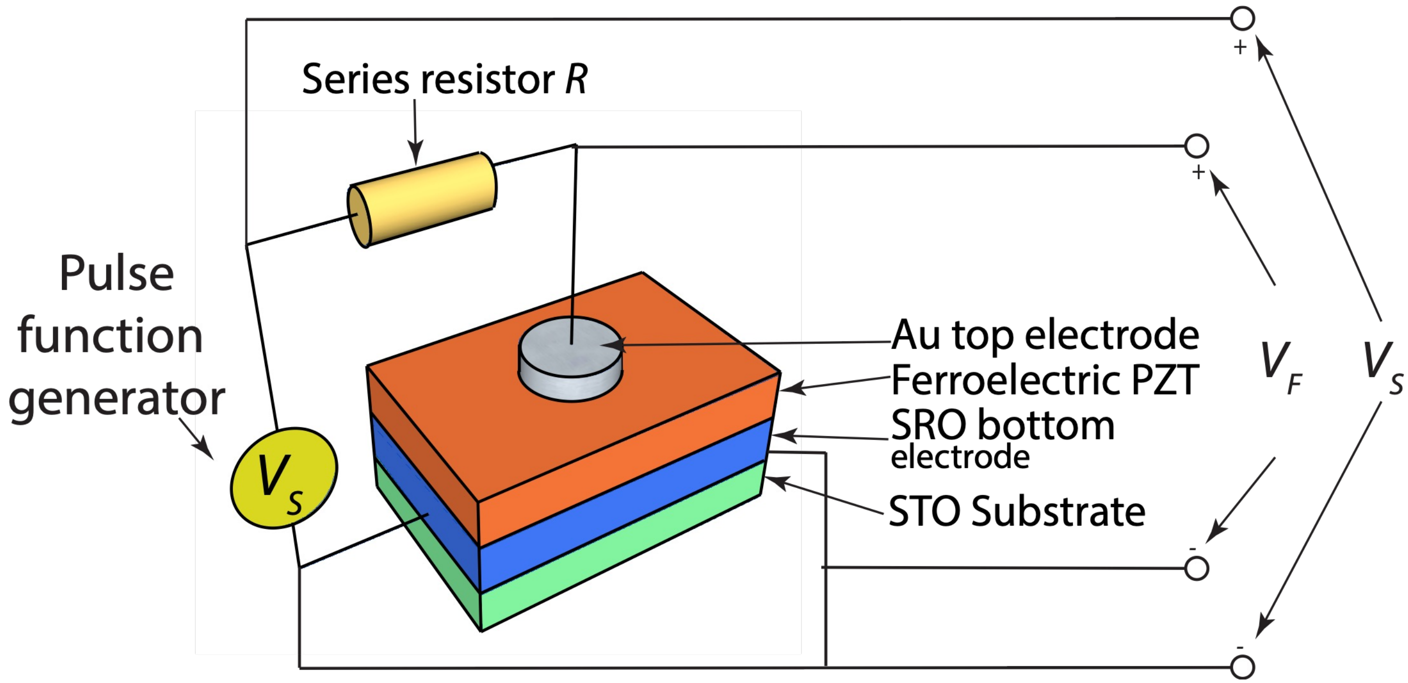


Experimental Setup for Brain Like Response

Circuit Diagram



Experimental Setup



A ferroelectric capacitor connected in series with an external resistor.

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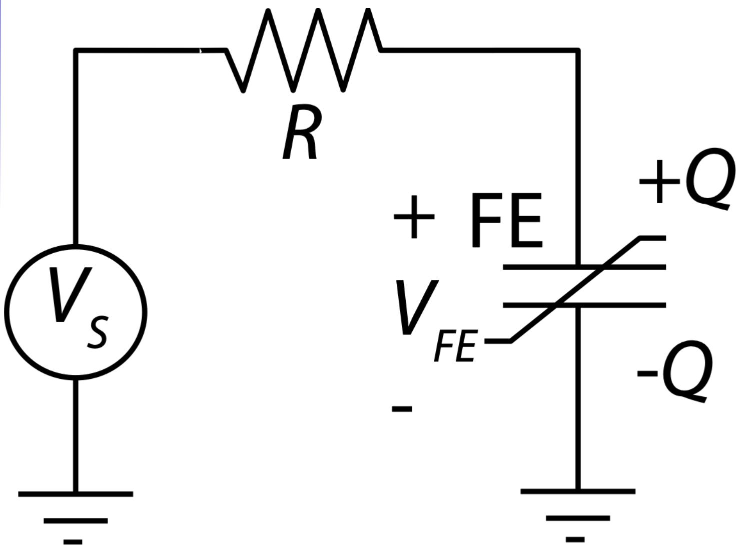
Experimental Setup



Ferroelectric

$Pb(Zr_{0.2}Ti_{0.8})O_3$ (60 nm)

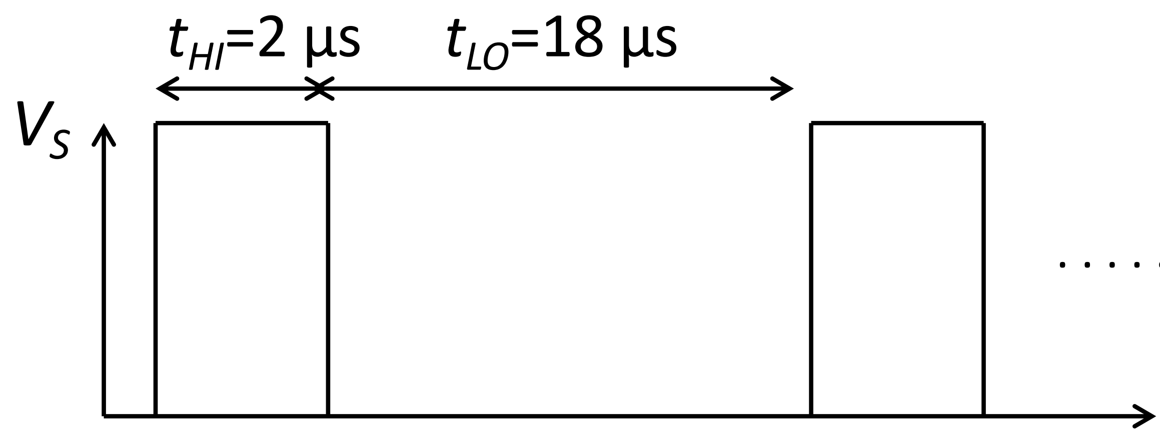
Area= $(50\ \mu m)^2$

R= 100 kΩ

# of Pulses=150

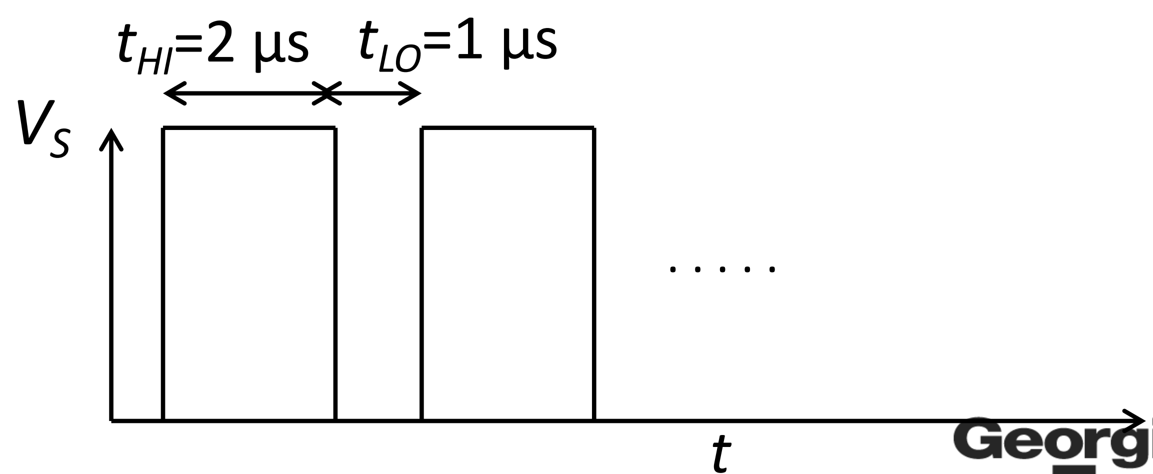
In frequent rehearsal: Short Term Plasticity

Repetition rate f_{rep}=50 kHz

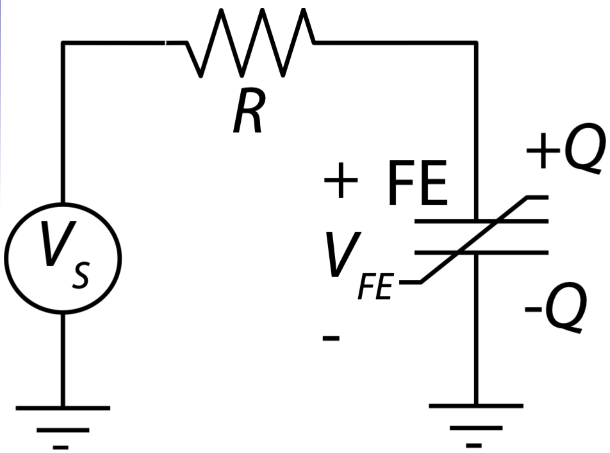


Frequent rehearsal: Long Term Potentiation

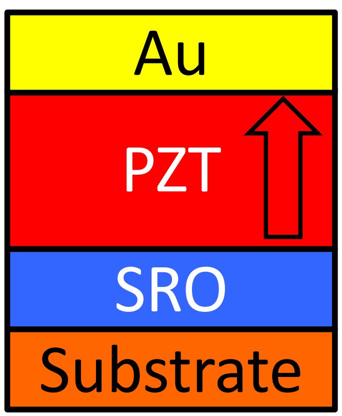
Repetition rate f_{rep} =333 kHz

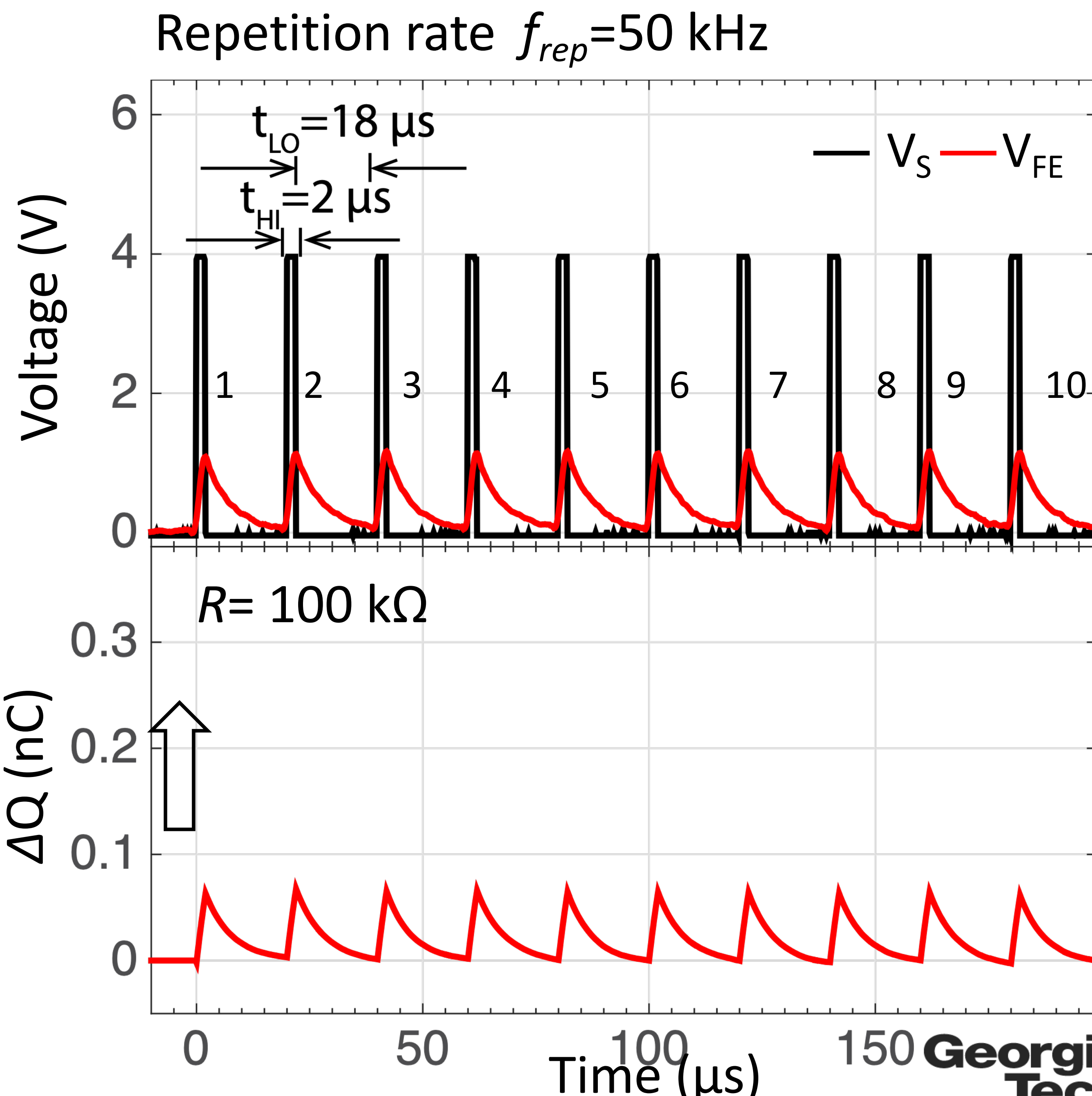


Short Term Plasticity: Experiment

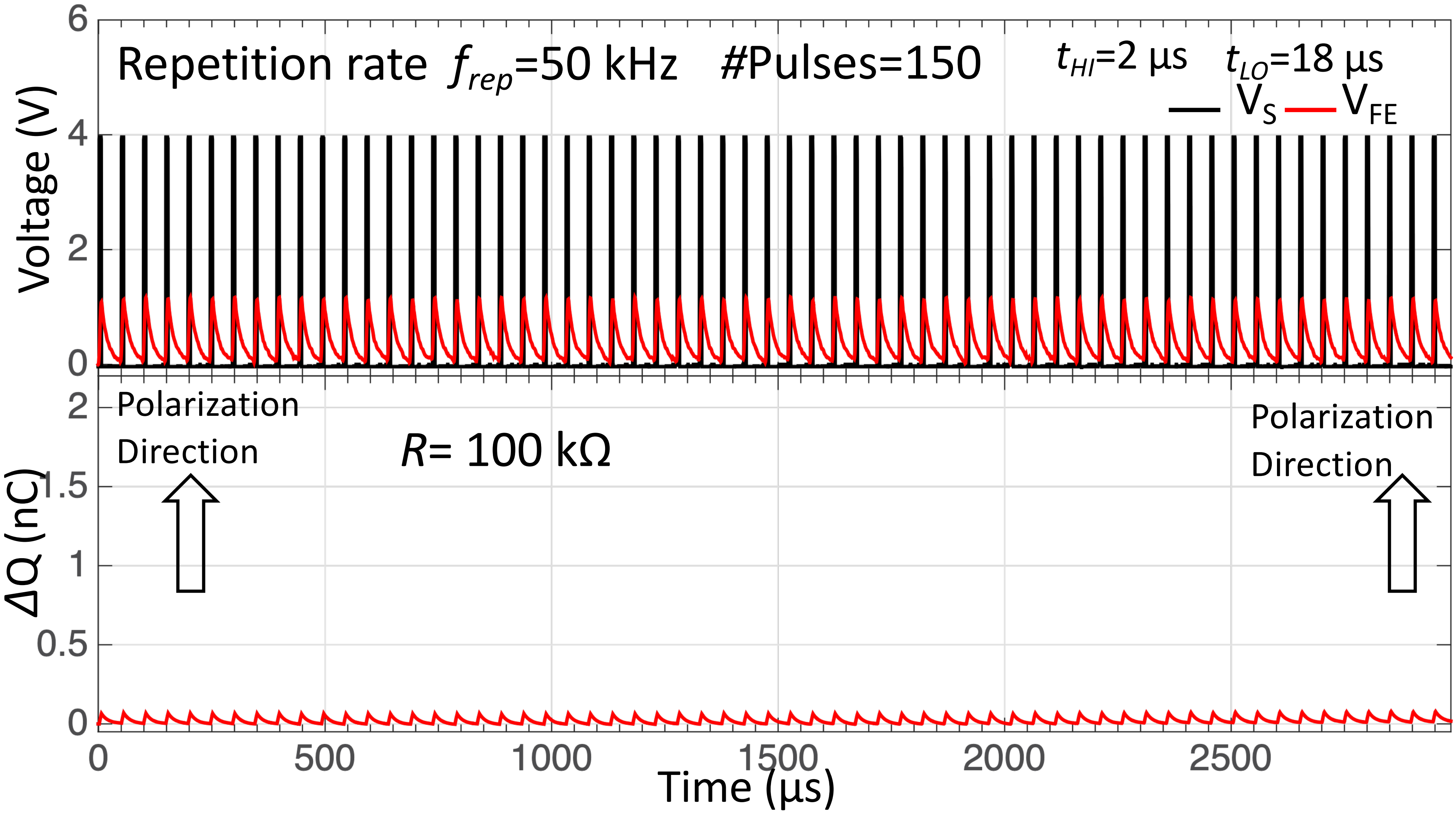


Initial Polarization Direction



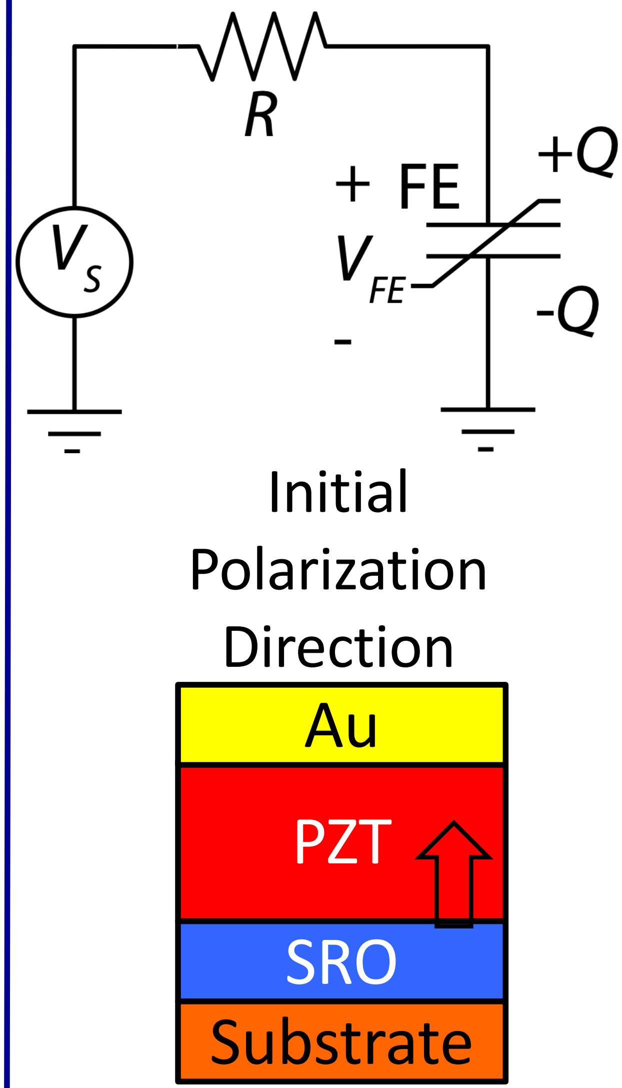


Short Term Plasticity: Experiment

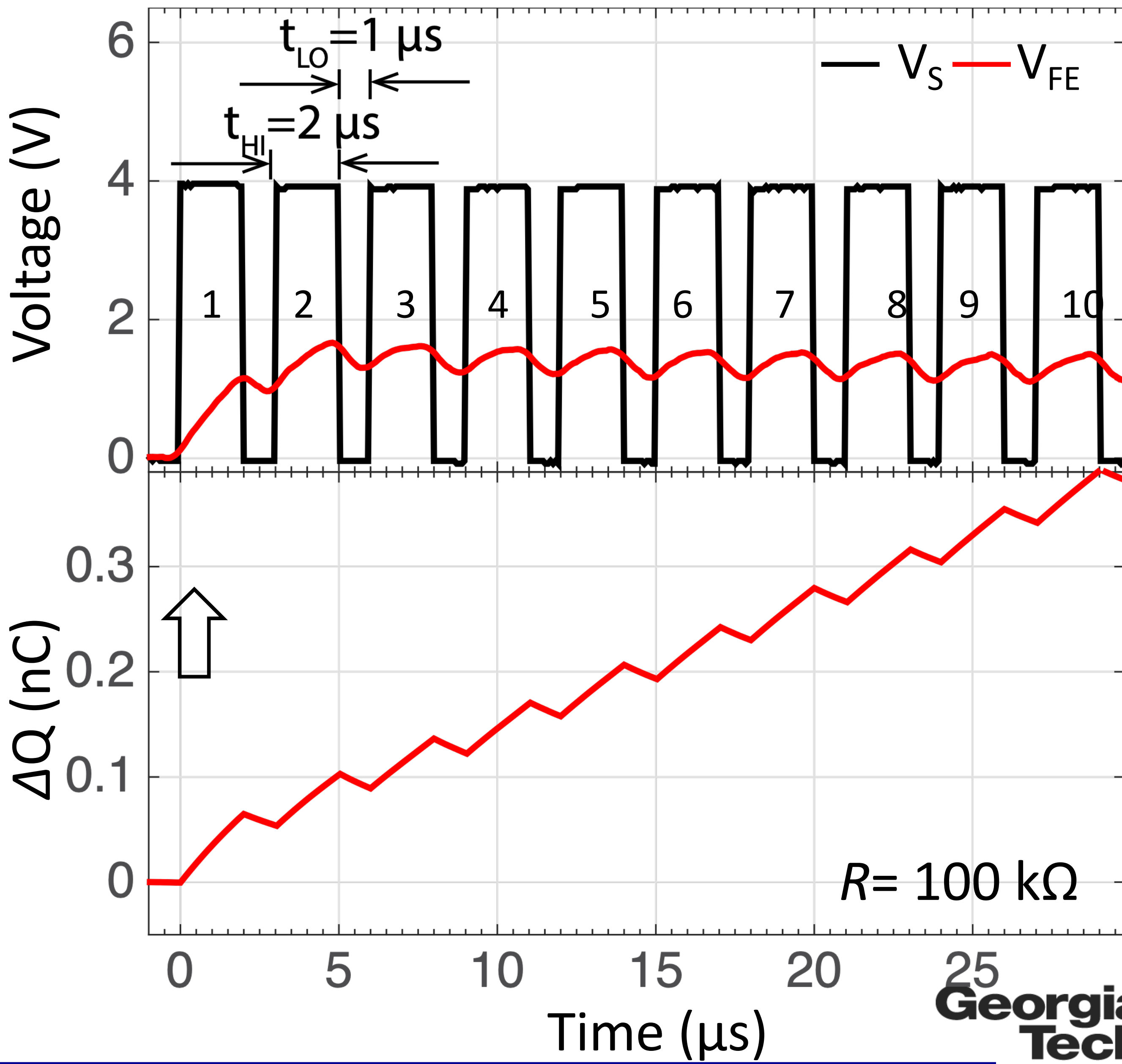


Repetition rate of 50 kHz delay does NOT switch the ferroelectric (no learning)!

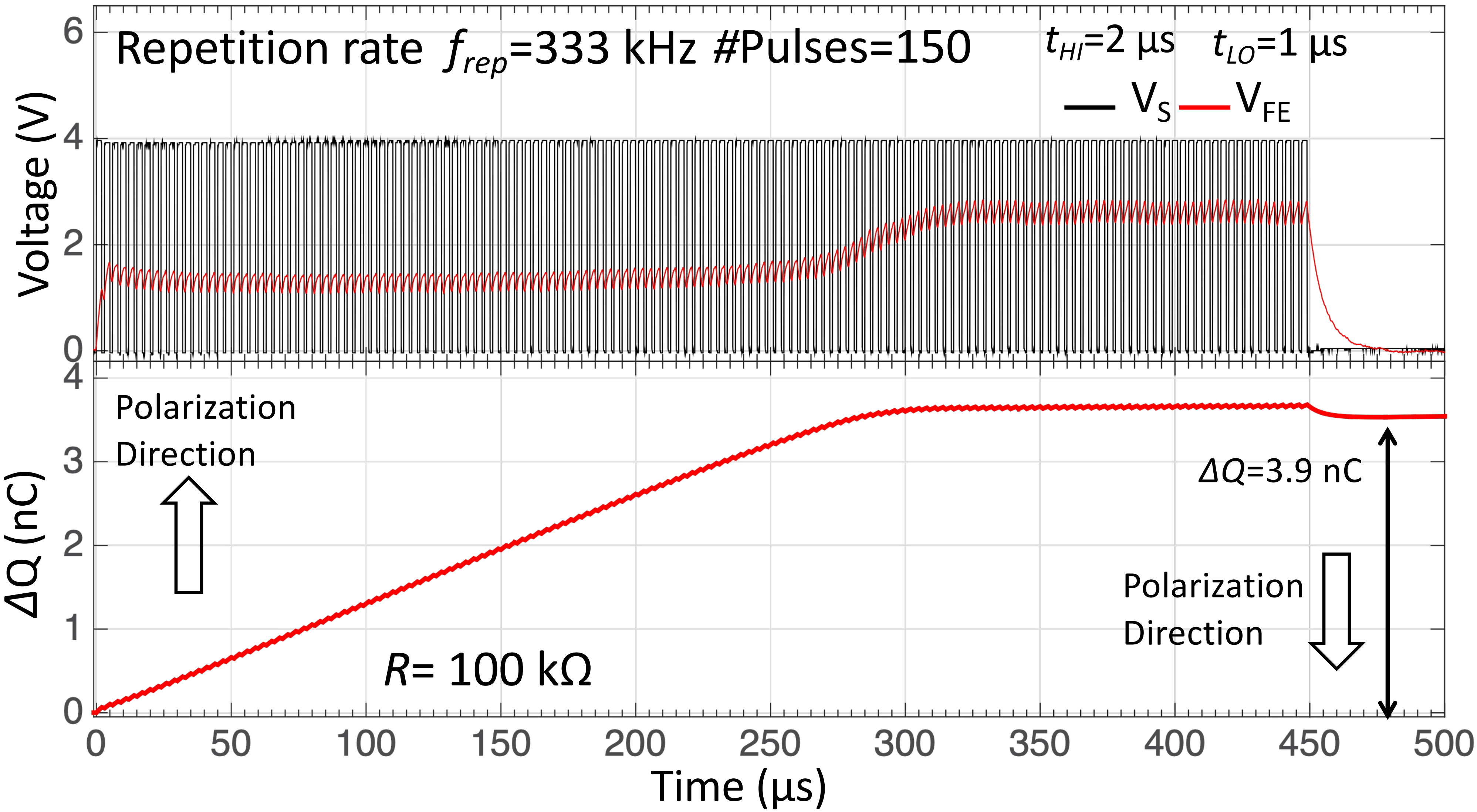
Long Term Potentiation: Experiment



Repetition rate f_{rep}=333 kHz

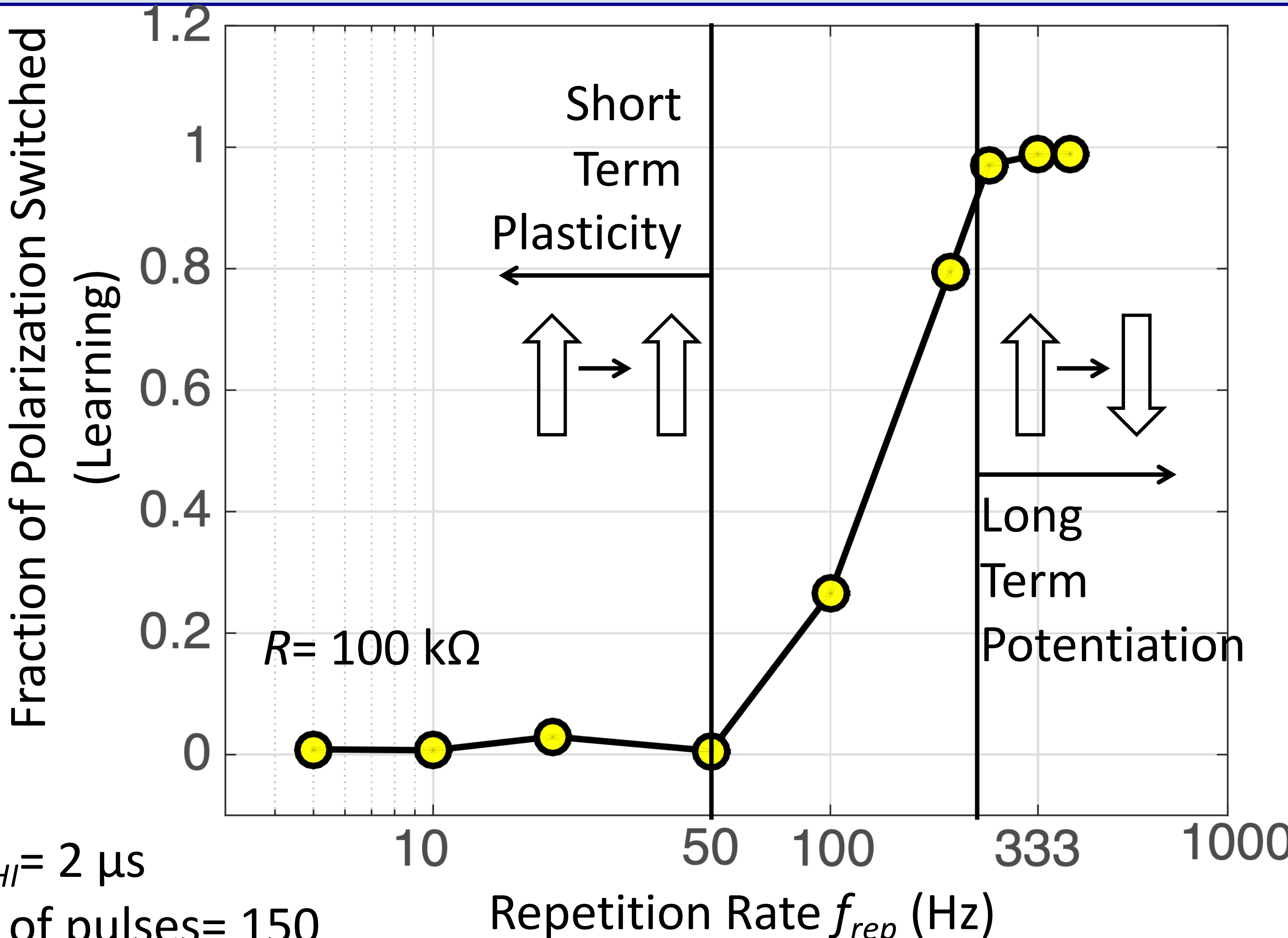


Long Term Potentiation: Experiment



Repetition rate of 333 kHz delay switches the ferroelectric (learning)!

Repetition Rate Dependent Learning

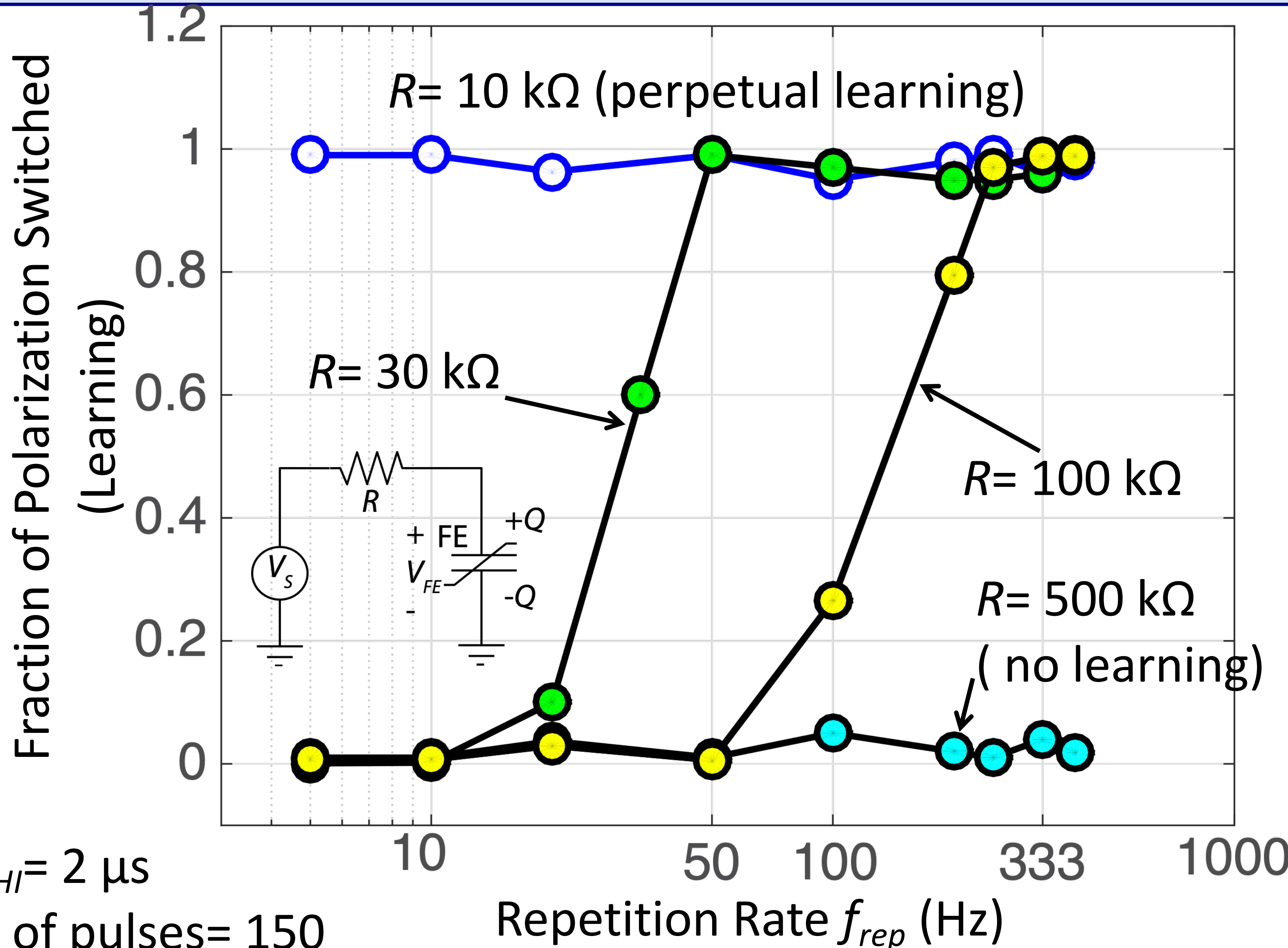


t_{HI}= 2 µs

# of pulses= 150

Learning dependents on repetition rate!

Repetition Rate Dependent Learning

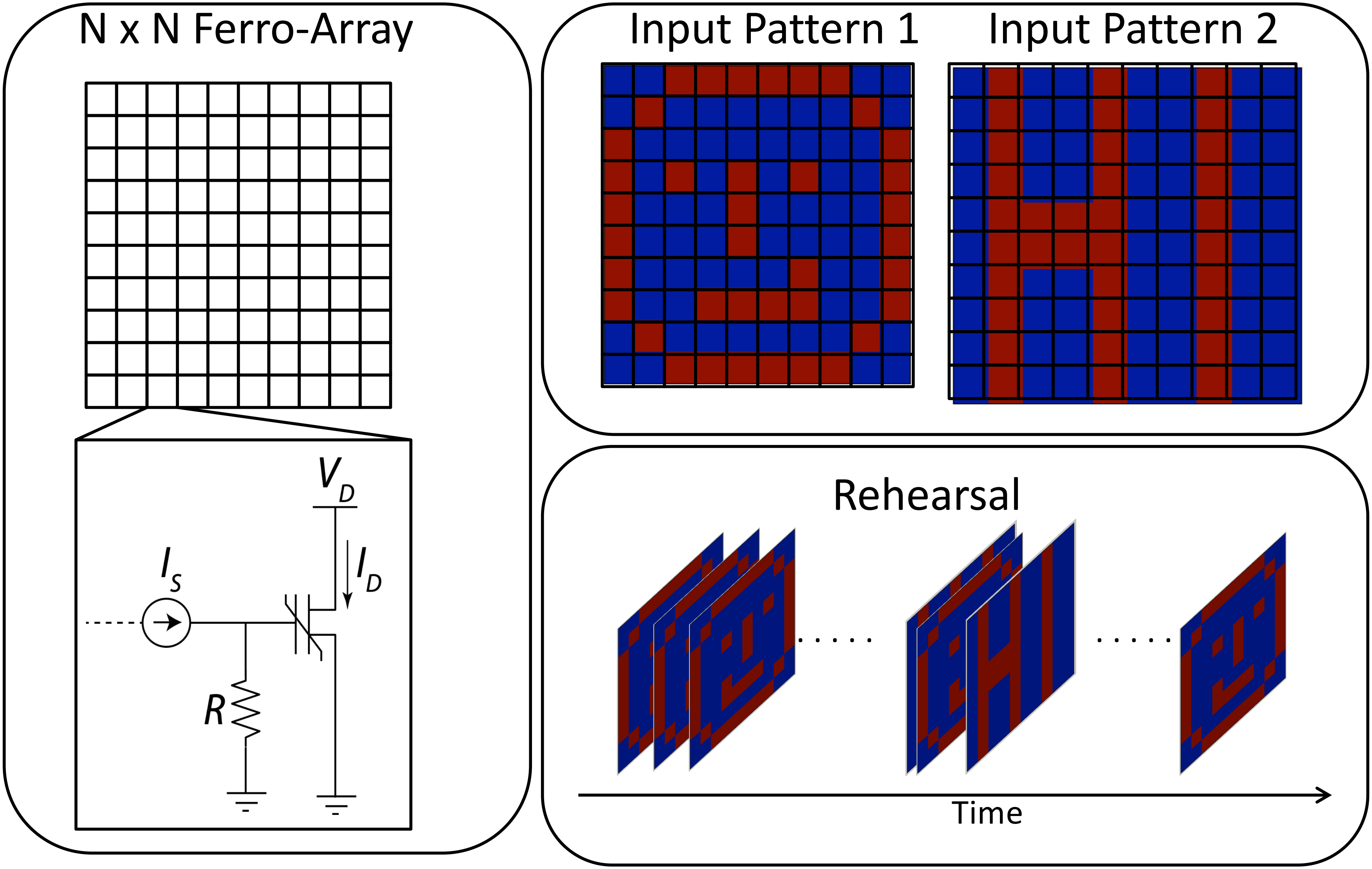


t_{HI}= 2 µs

# of pulses= 150

Learning behavior can be tuned by circuit parameters!

Pattern memorization using ferro-array



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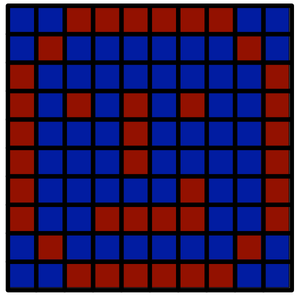
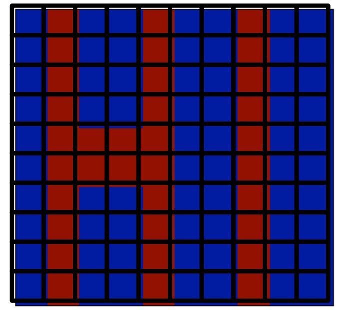
Pattern memorization using ferro-array

Input Pattern 1

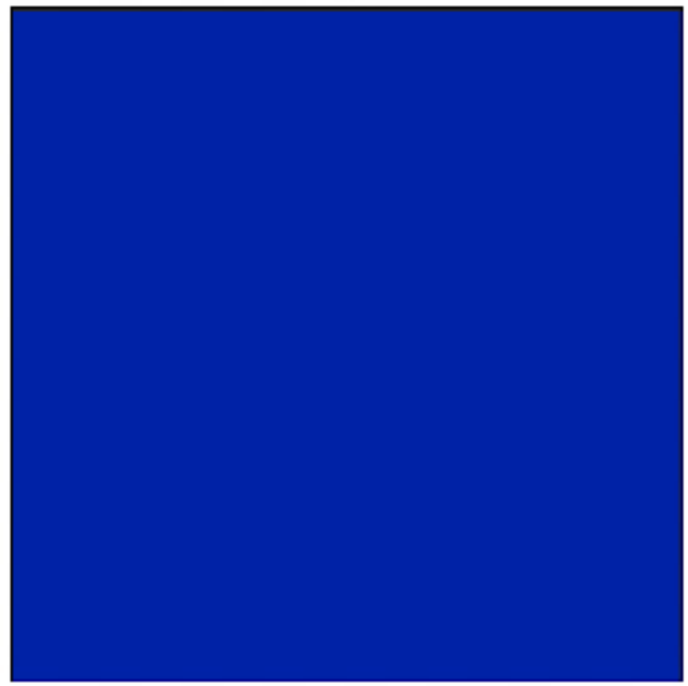


Input Pattern 2



Input Pattern

Memory State



No learning of any patterns!

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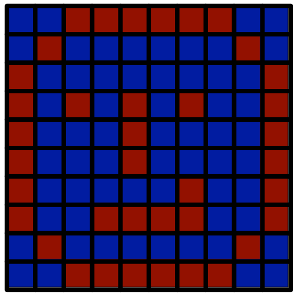
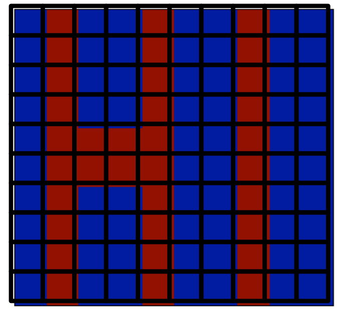
Pattern memorization using ferro-array

Input Pattern 1



Input Pattern 2



Input Pattern

Memory State

Learning of the more frequent pattern!

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Summary

Dynamics of Brain's Functional Units: **Neurons and Synapse**

Dynamics of **Memory Materials & Devices**

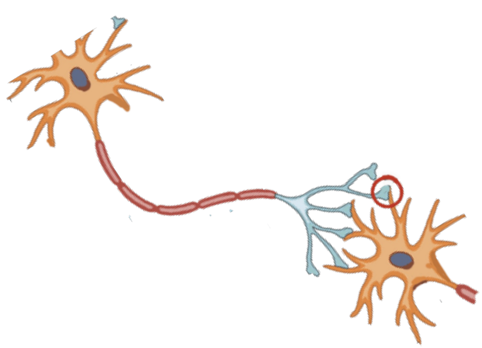
New Computational Capabilities

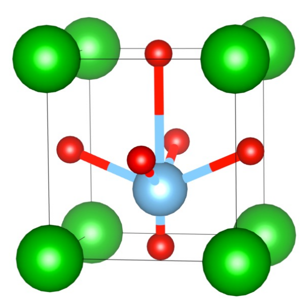
- Short Term Plasticity & Long Term Potentiation
- Theoretical Framework

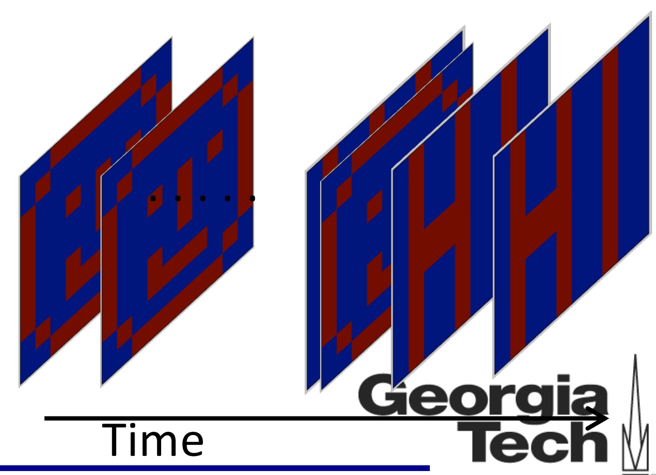
Ferroelectric Memory:

- Landau-Khalatnikov Dynamics of Ferroelectric
- Experimental realization

Possible Application in Pattern Memorization, Recognition







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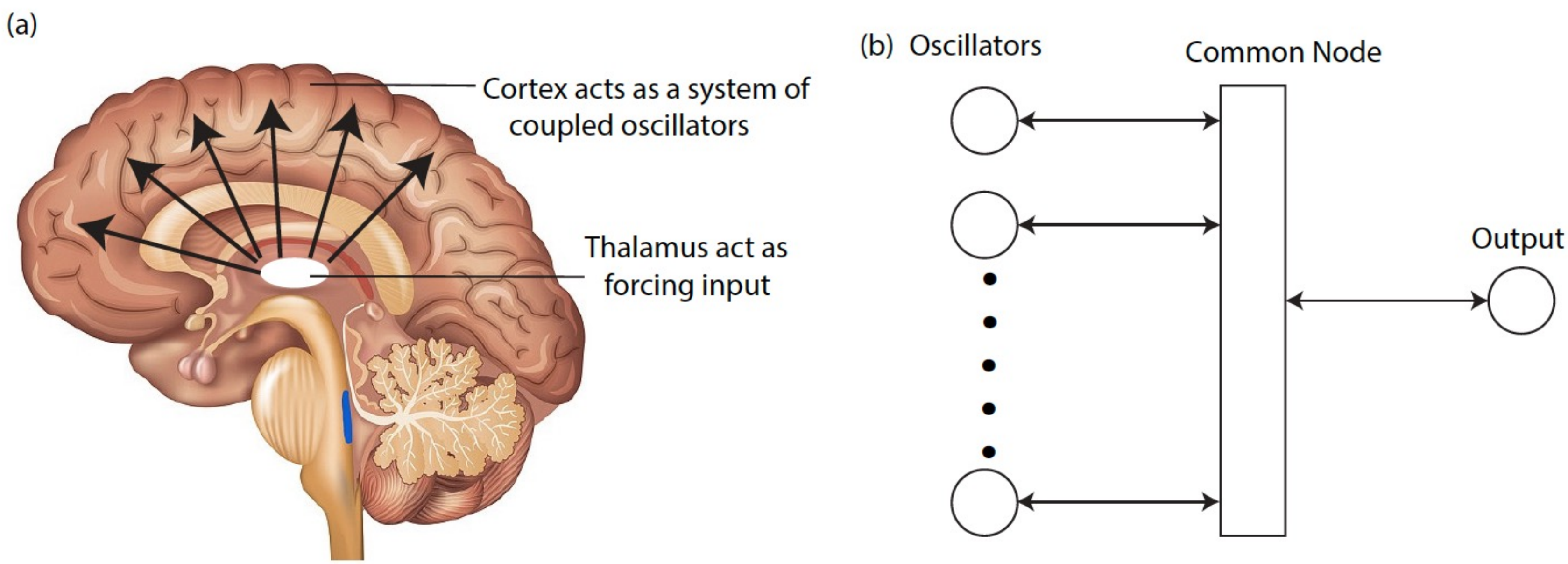
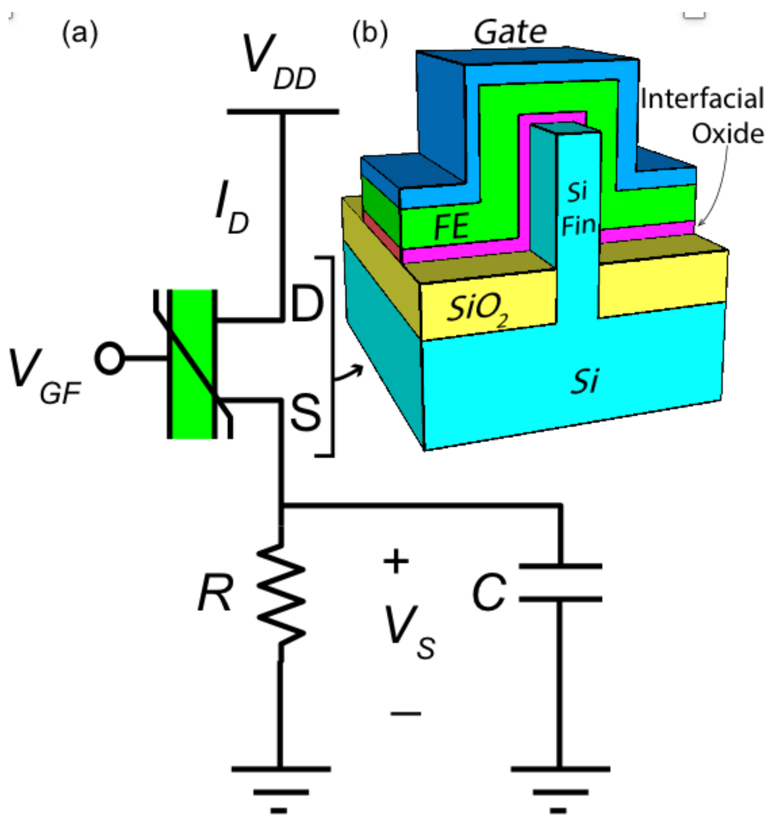
Coupled Ferroelectric Oscillator

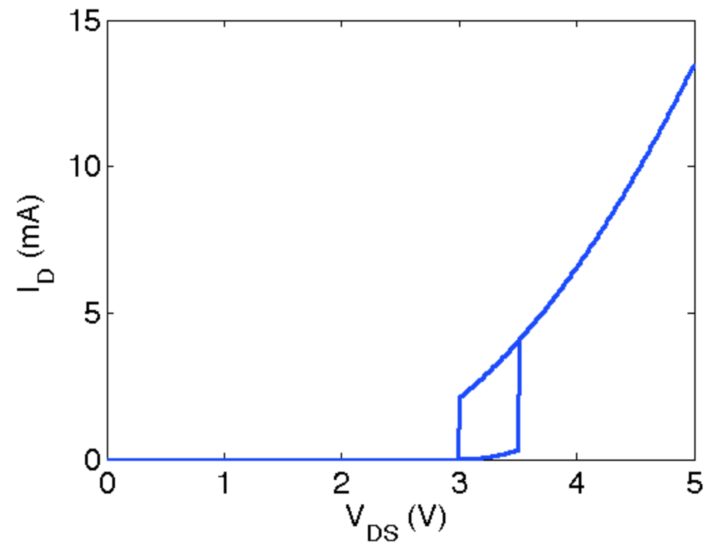


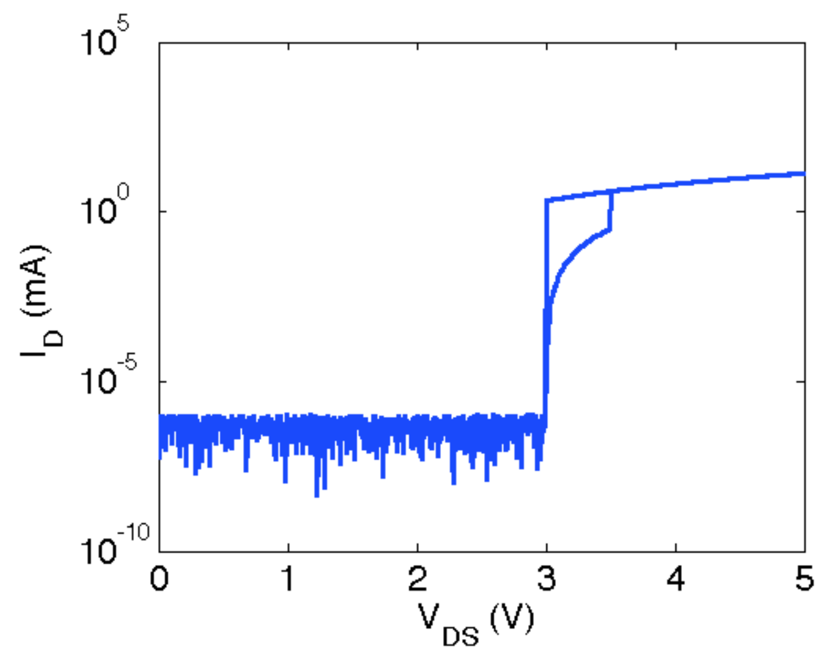
Synchronization dynamics can be utilized for computationally hard problems!

STT-MRAM
Metal Insulator Transition Materials

Coupled Ferroelectric Oscillator







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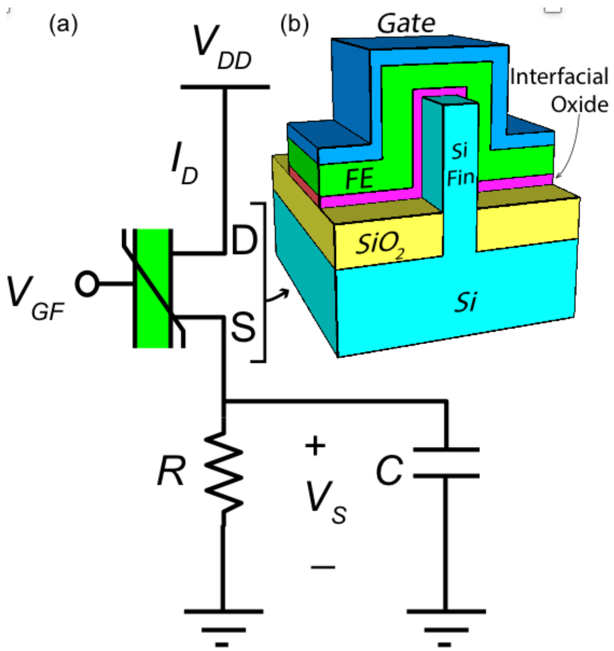
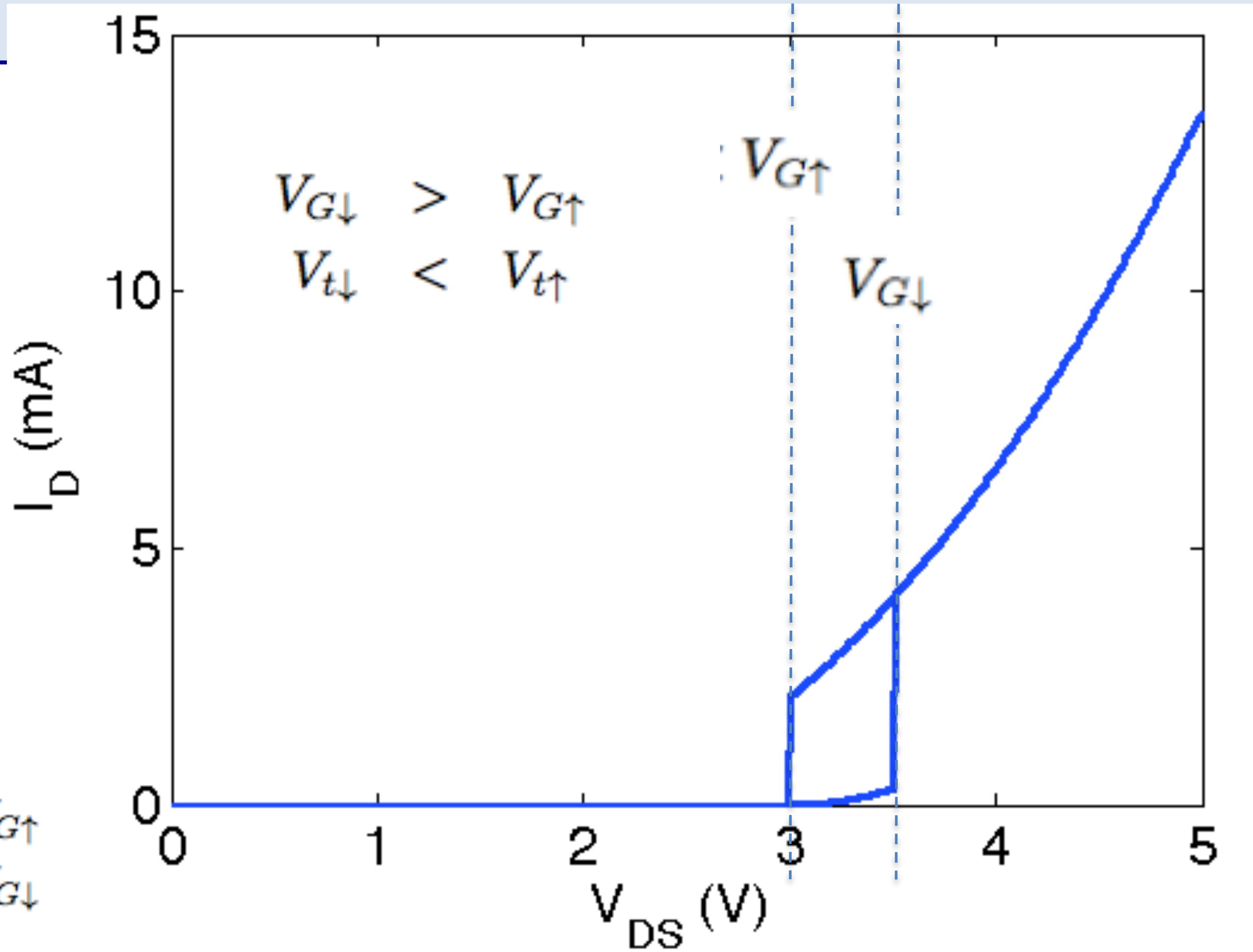
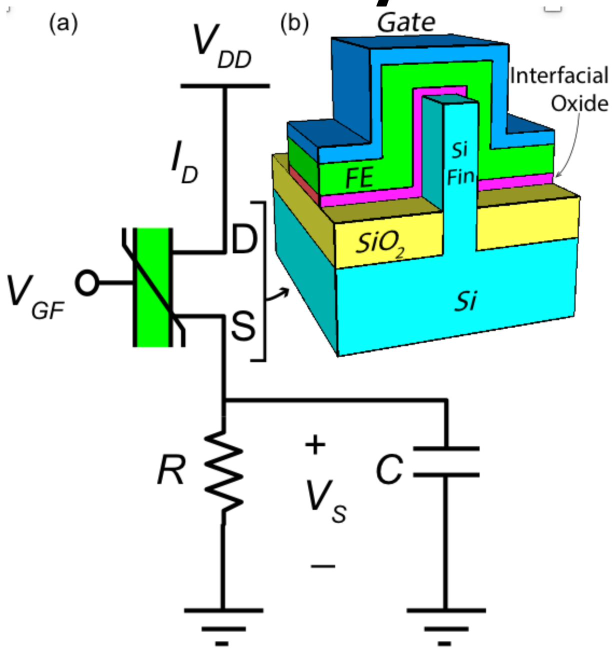


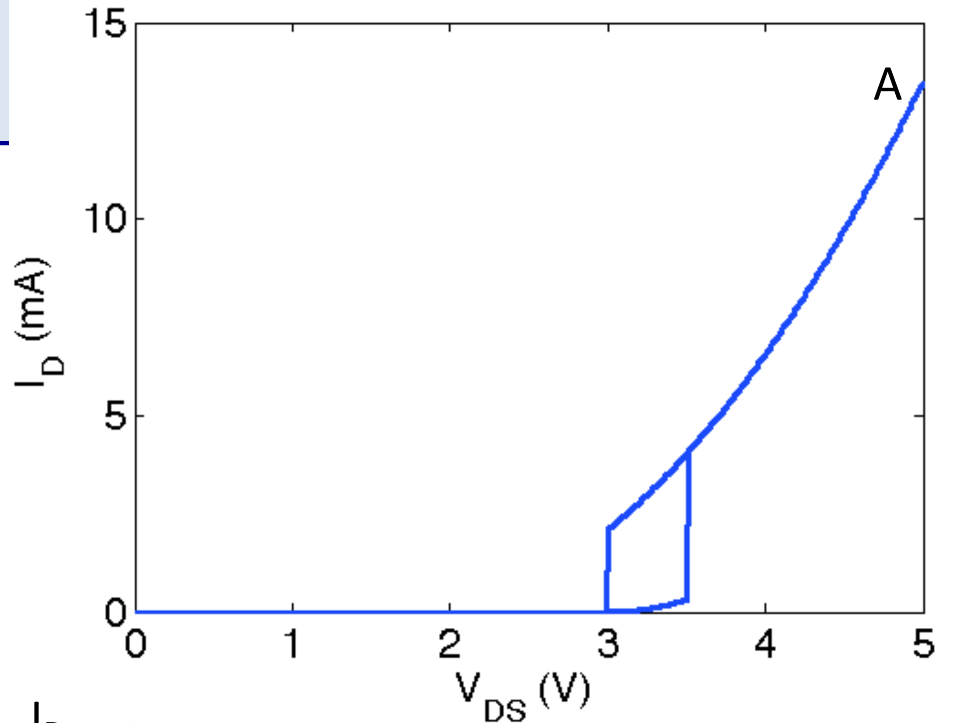


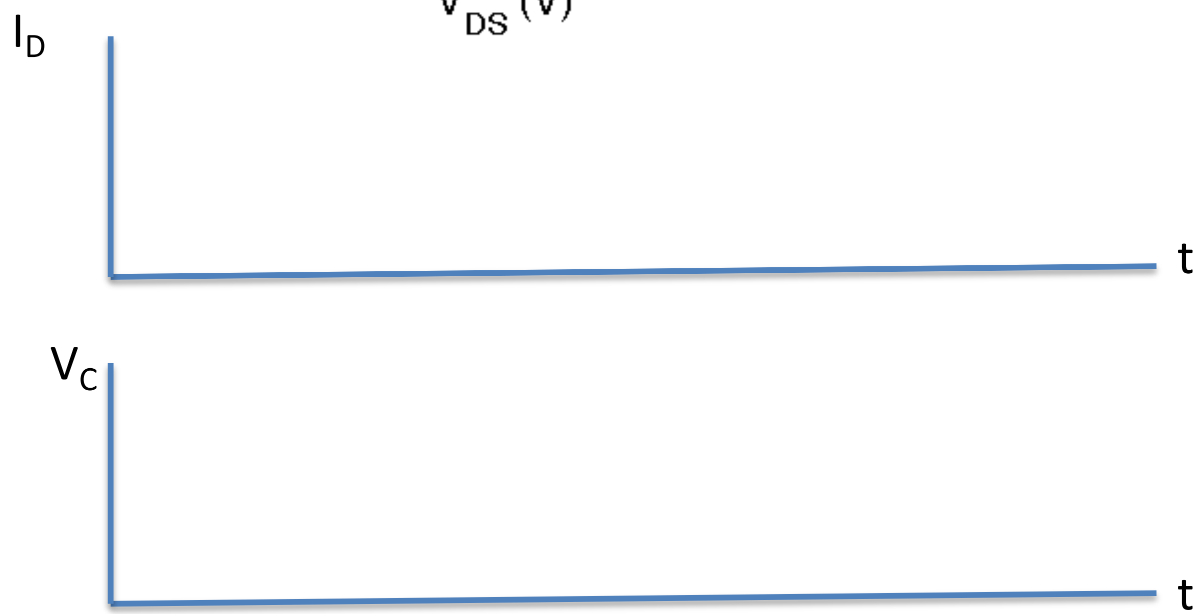
$$
\begin{aligned}
V_t &= V_{t\uparrow} \text{ ,when } V_{GS} < V_{G\uparrow} \\
&= V_{t\downarrow} \text{ ,when } V_{GS} > V_{G\downarrow}
\end{aligned}
$$

$$
\begin{aligned}
I_D &= 0 \text{ ,when } V_{GS} - V_t < 0 \\
&= \frac{\mu C_{ox} W}{L}[(V_{GS} - V_t)V_{DS} - \frac{1}{2}V_{DS}^2] \text{ ,when } V_{GS} - V_t > V_{DS} \\
&= \frac{\mu C_{ox} W}{2L}(V_{GS} - V_t)^2 \text{ ,when } V_{GS} - V_t \leq V_{DS}
\end{aligned}
$$

Time Dynamics







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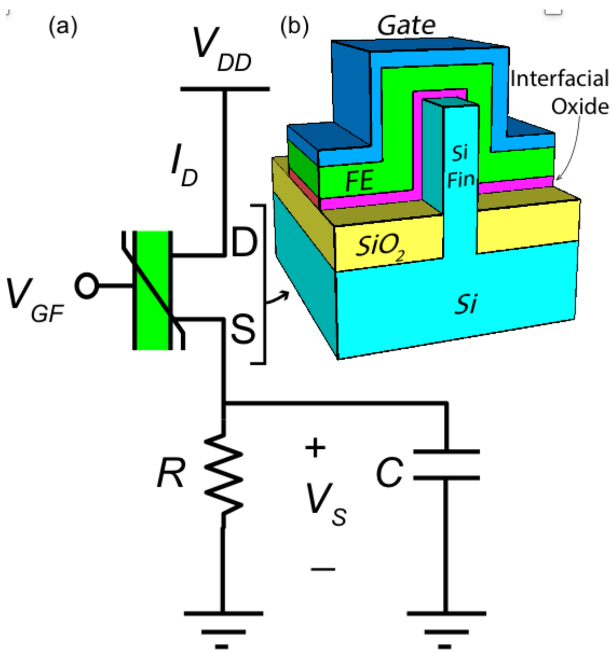
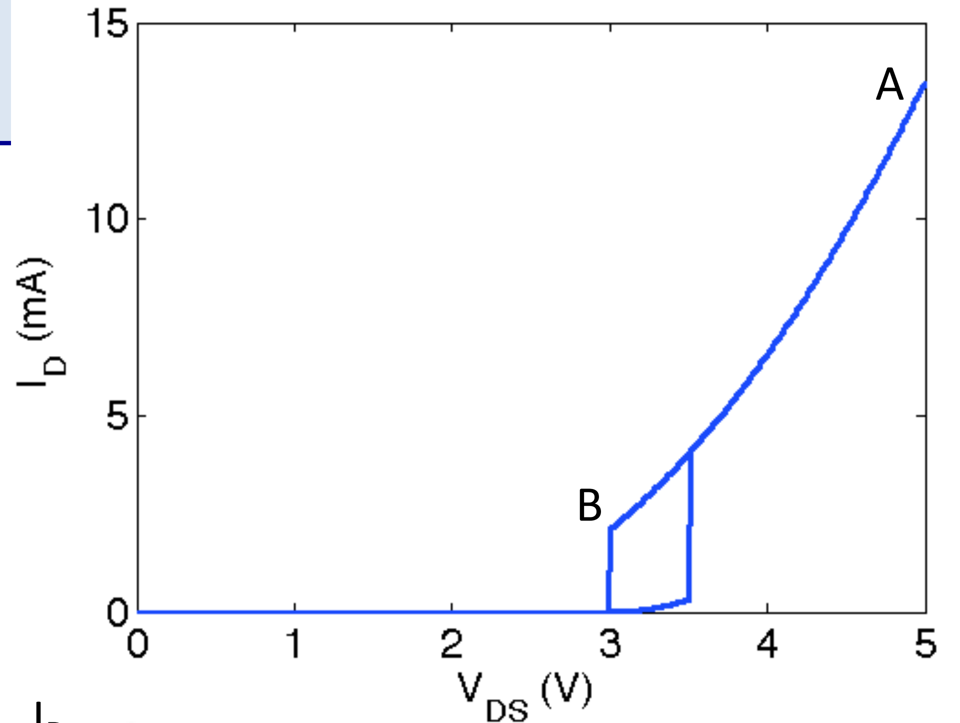
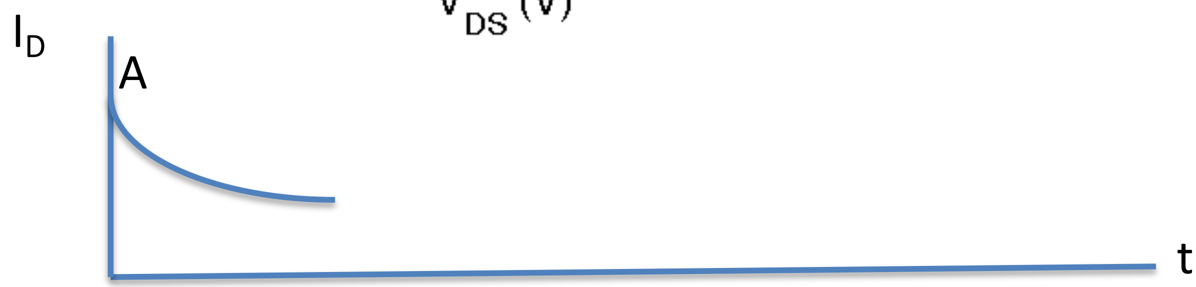
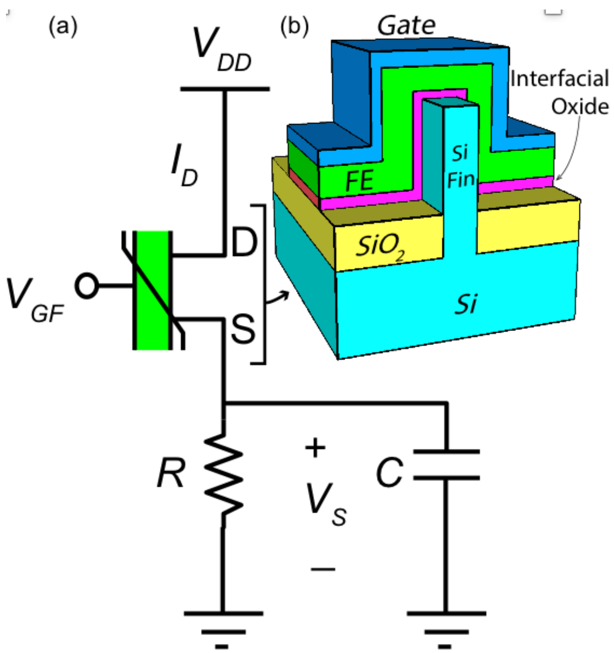
Time Dynamics

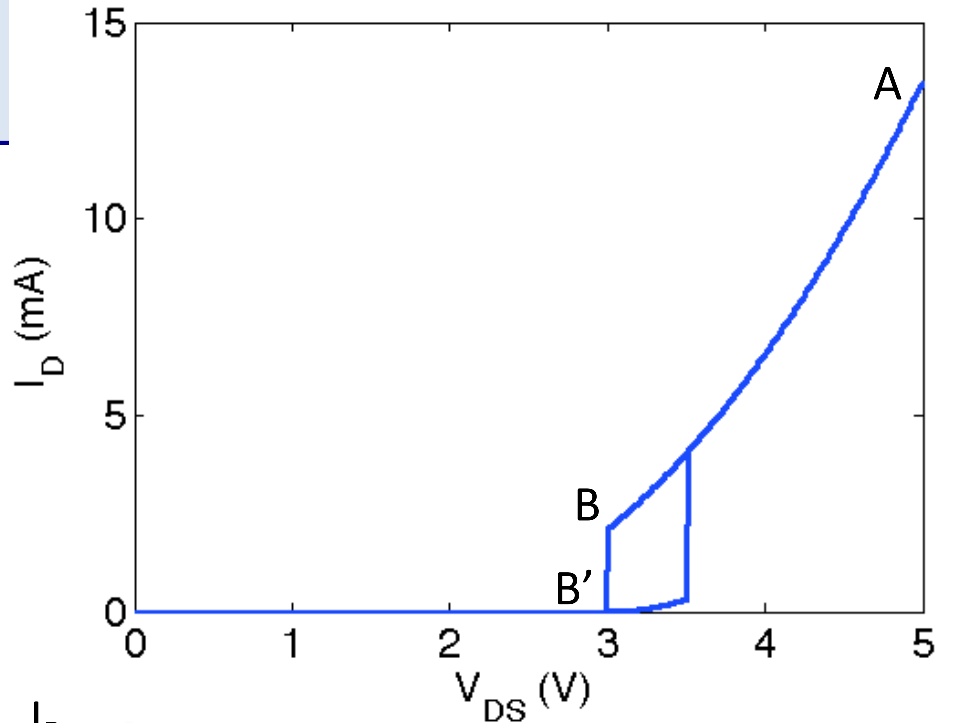


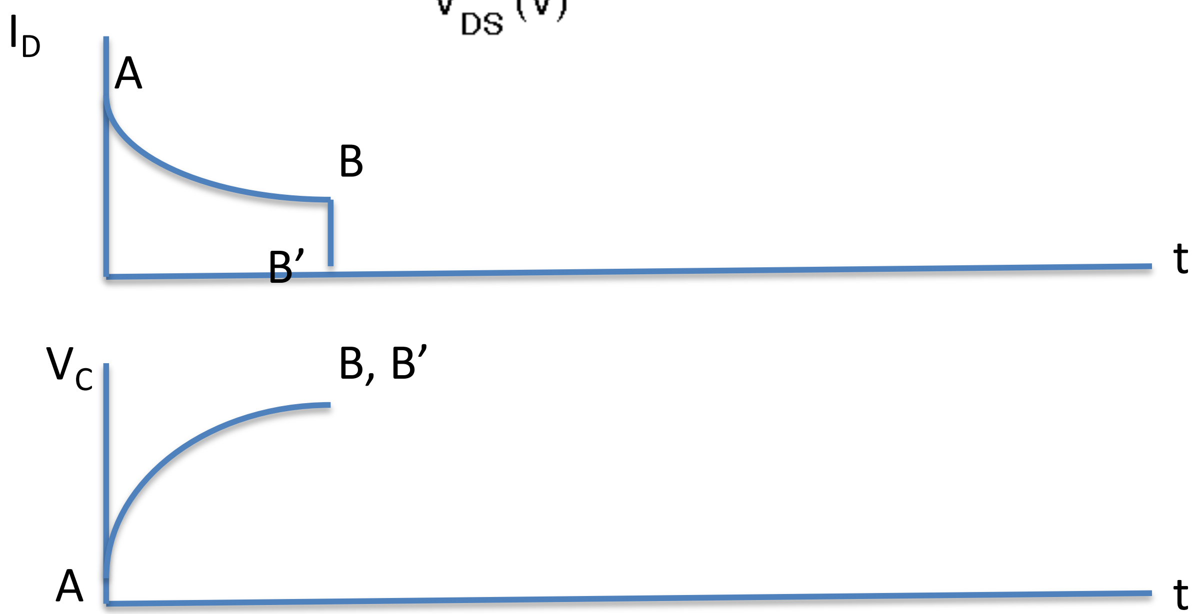




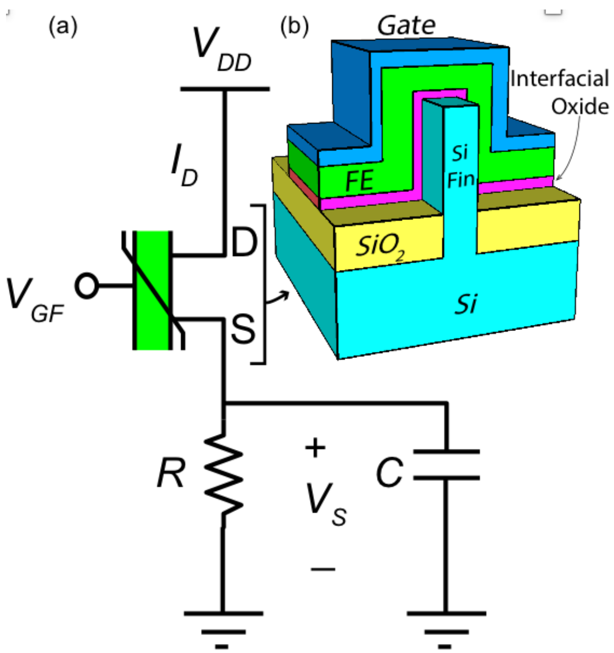
Time Dynamics

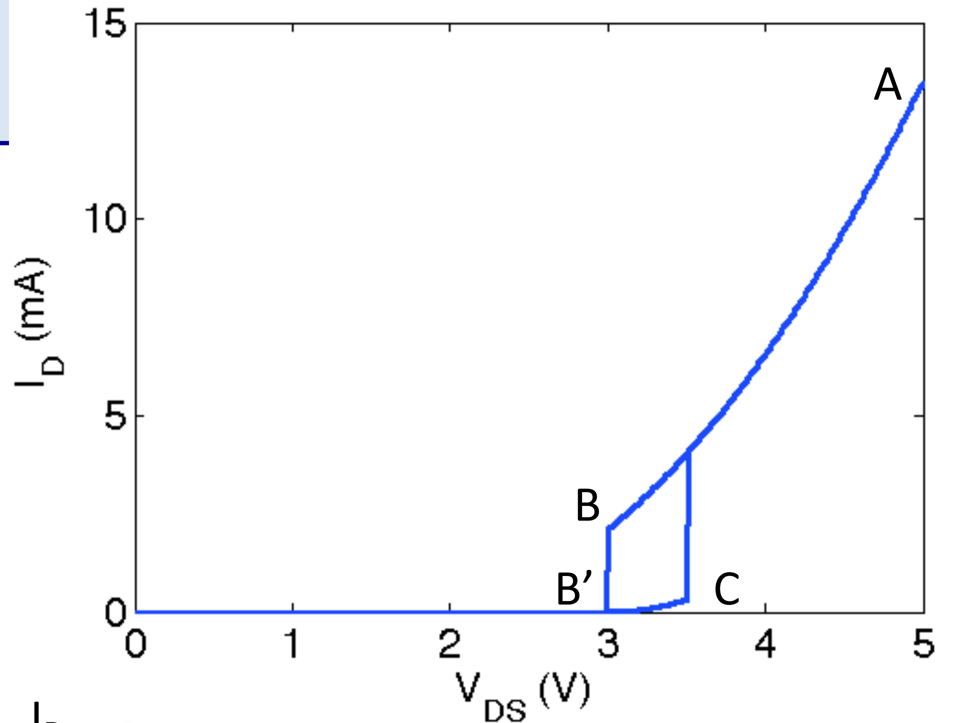


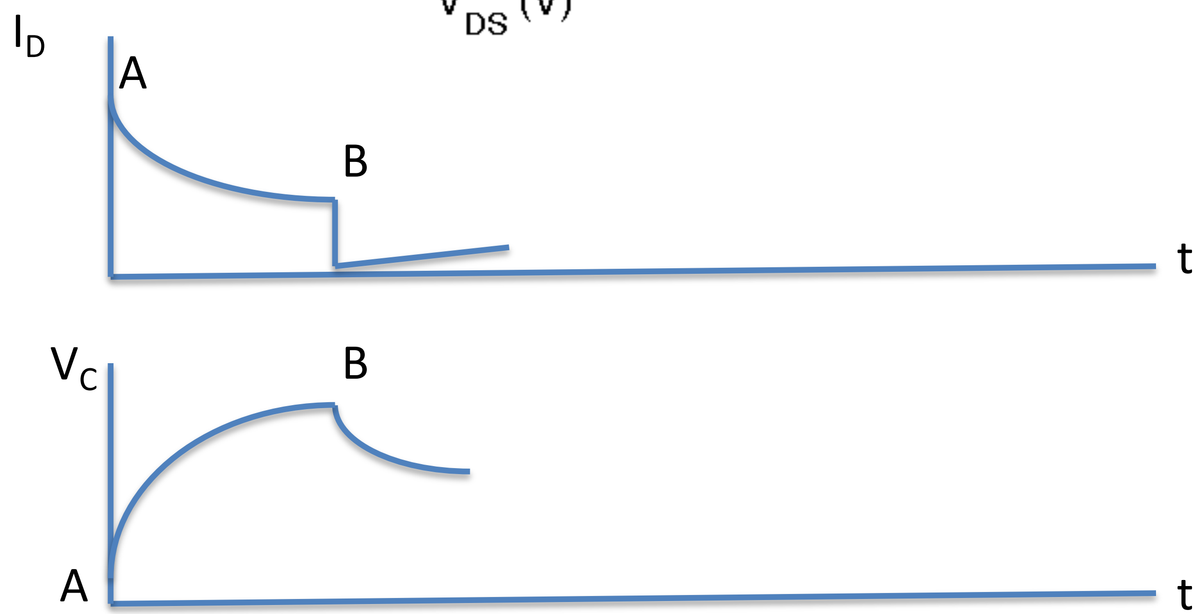




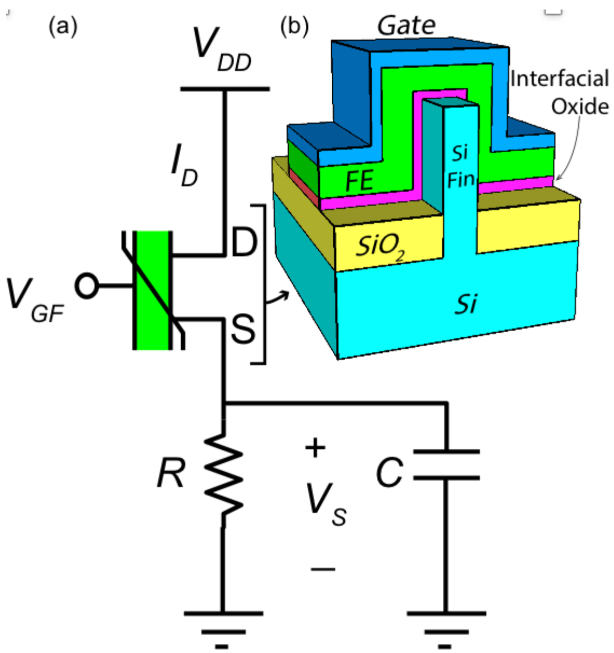
Time Dynamics

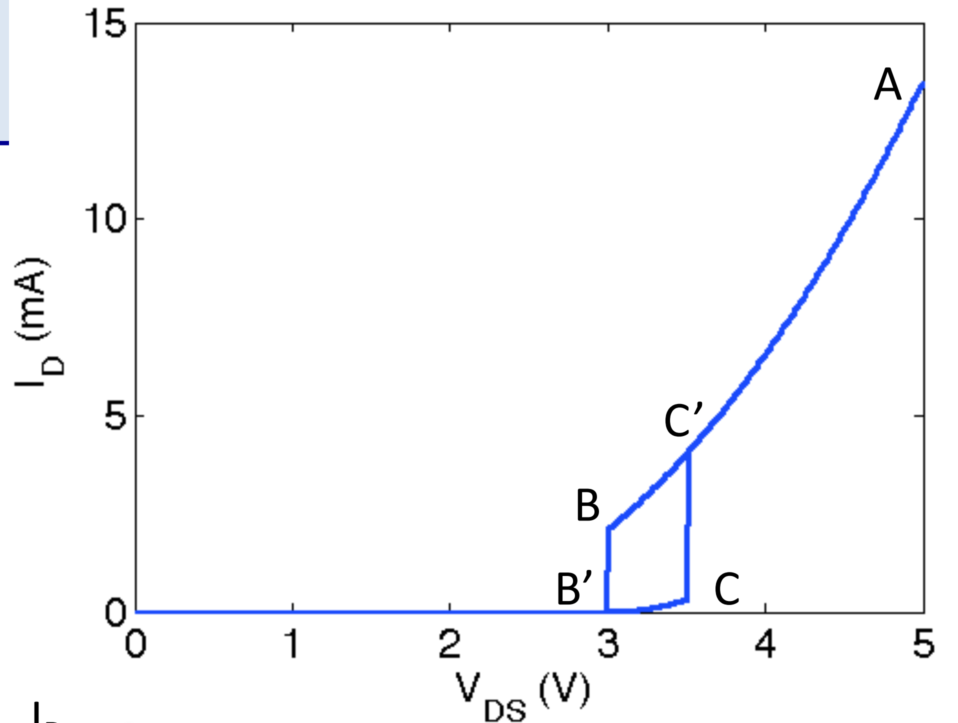


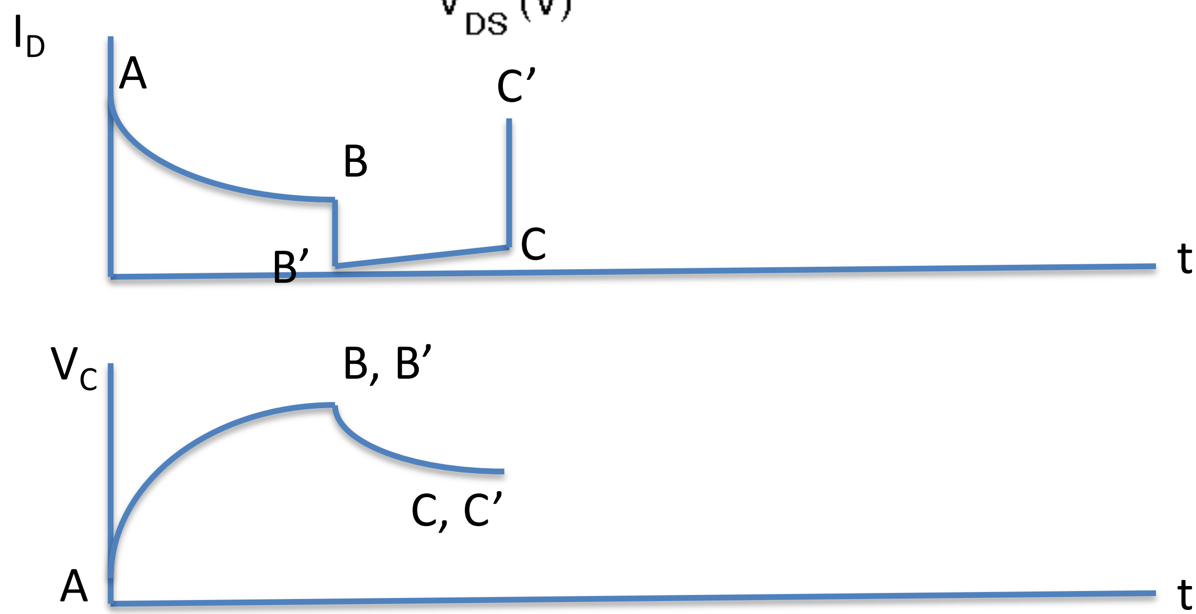




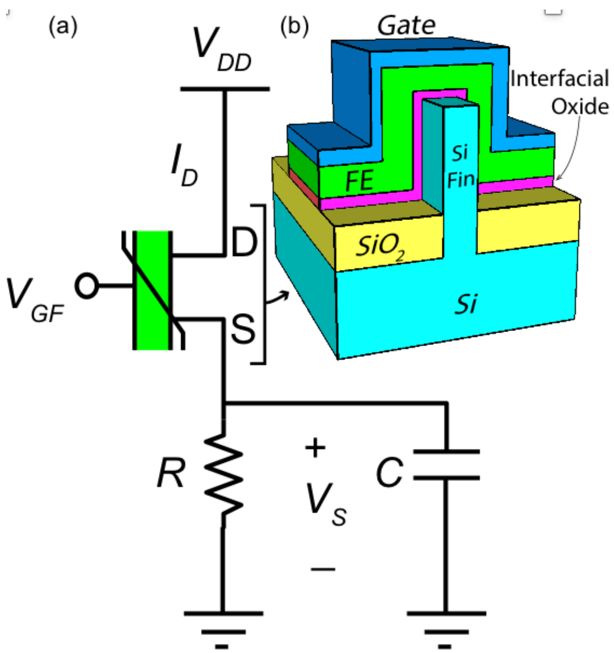
Time Dynamics

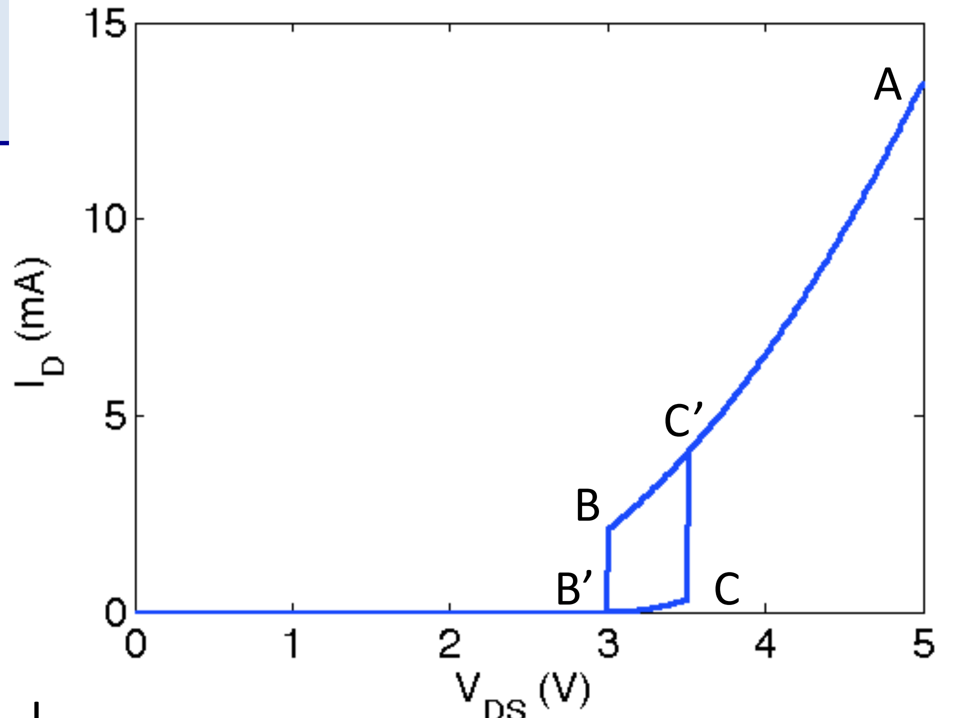


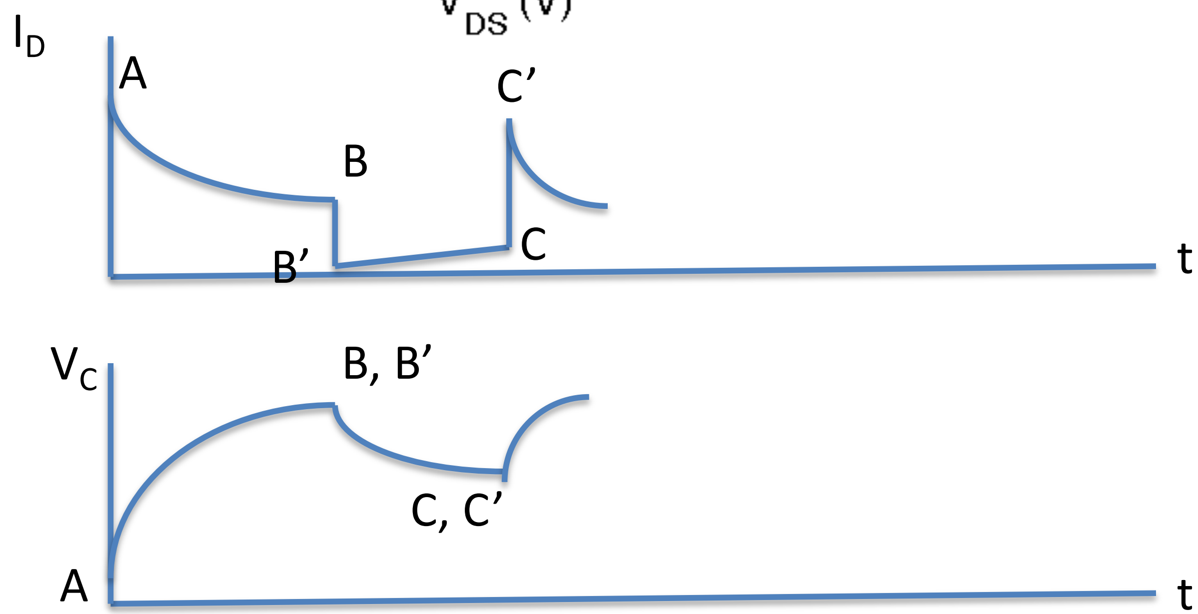




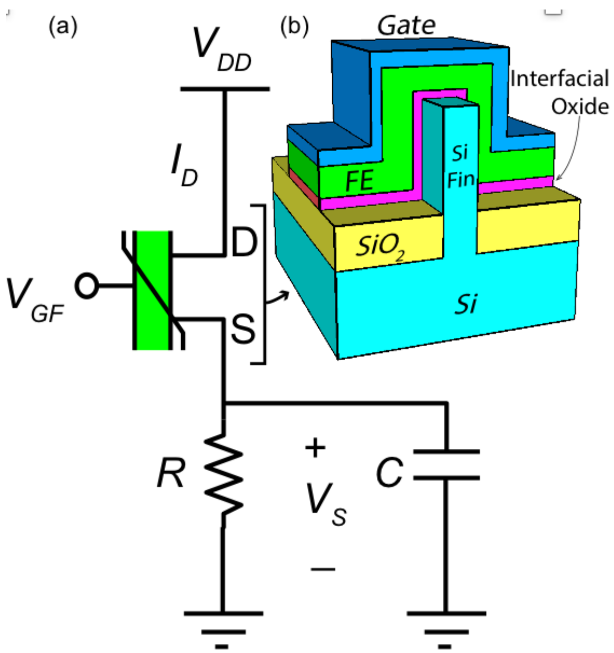
Time Dynamics

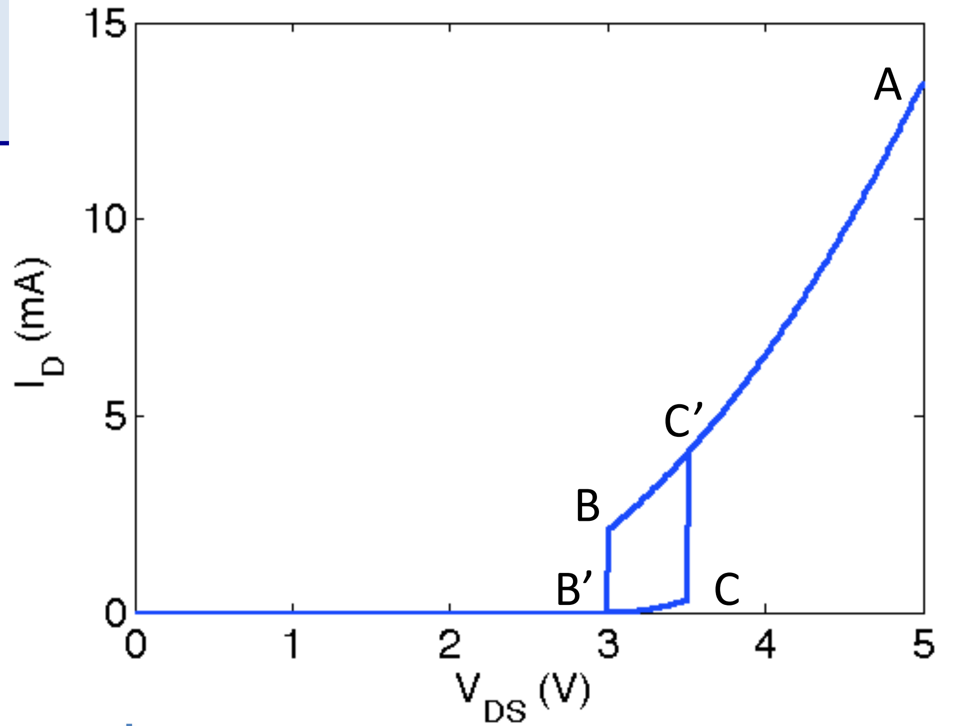


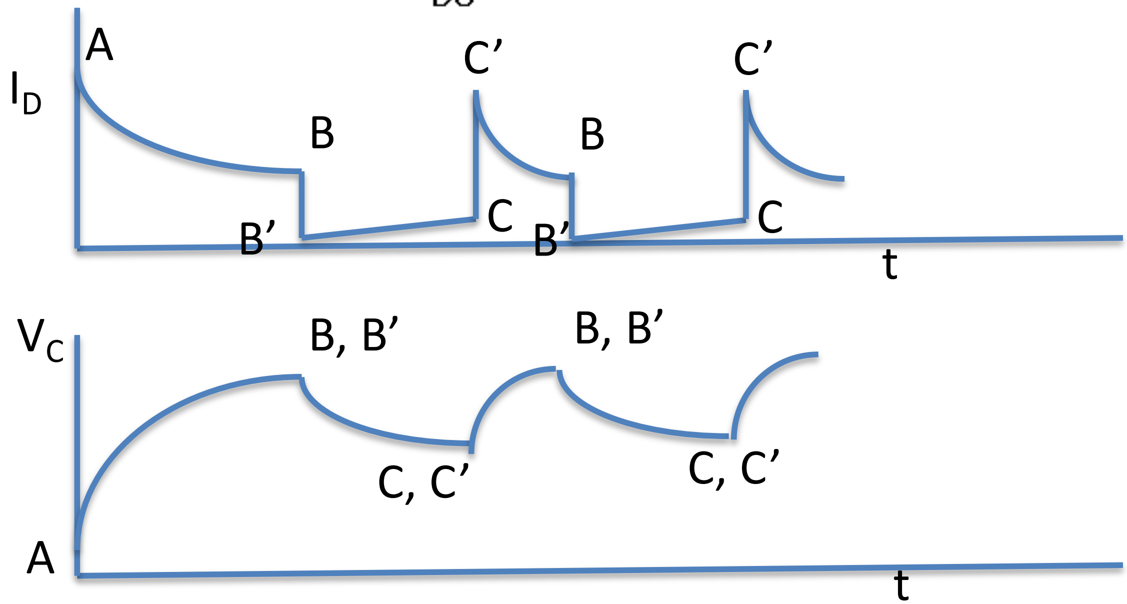




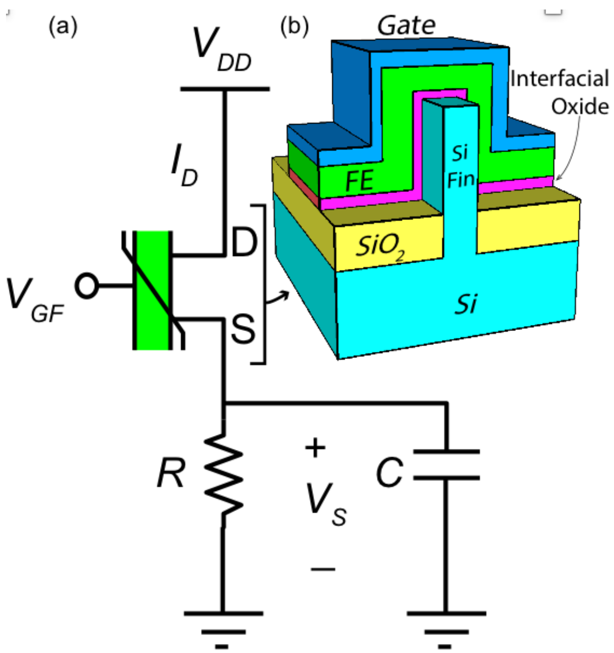
Time Dynamics

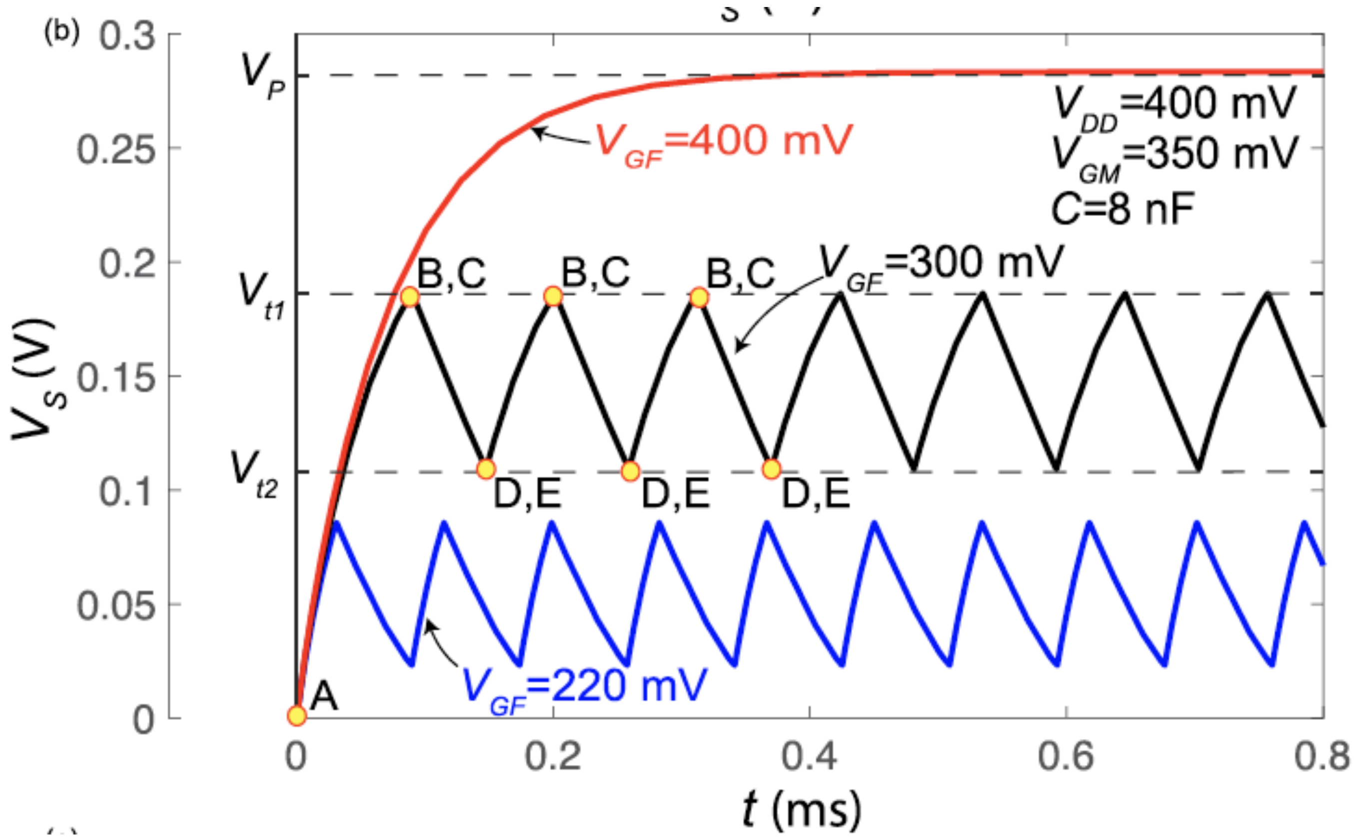




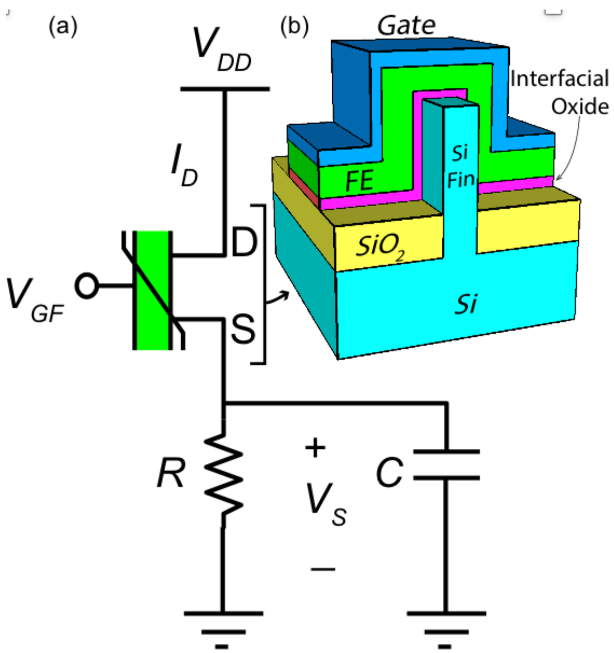


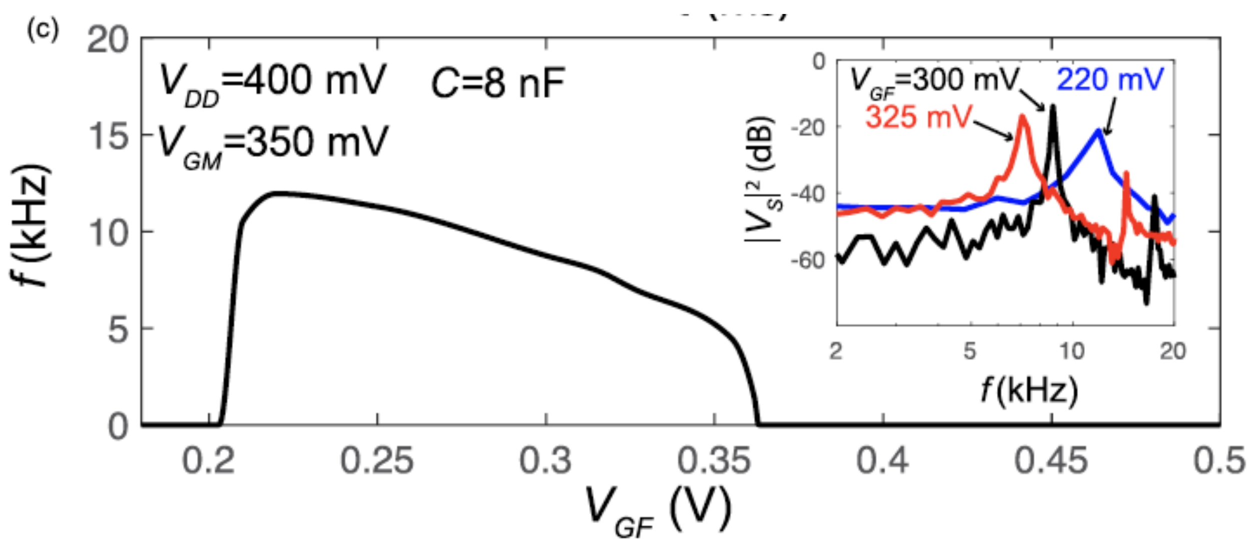
Ferroelectric Oscillator





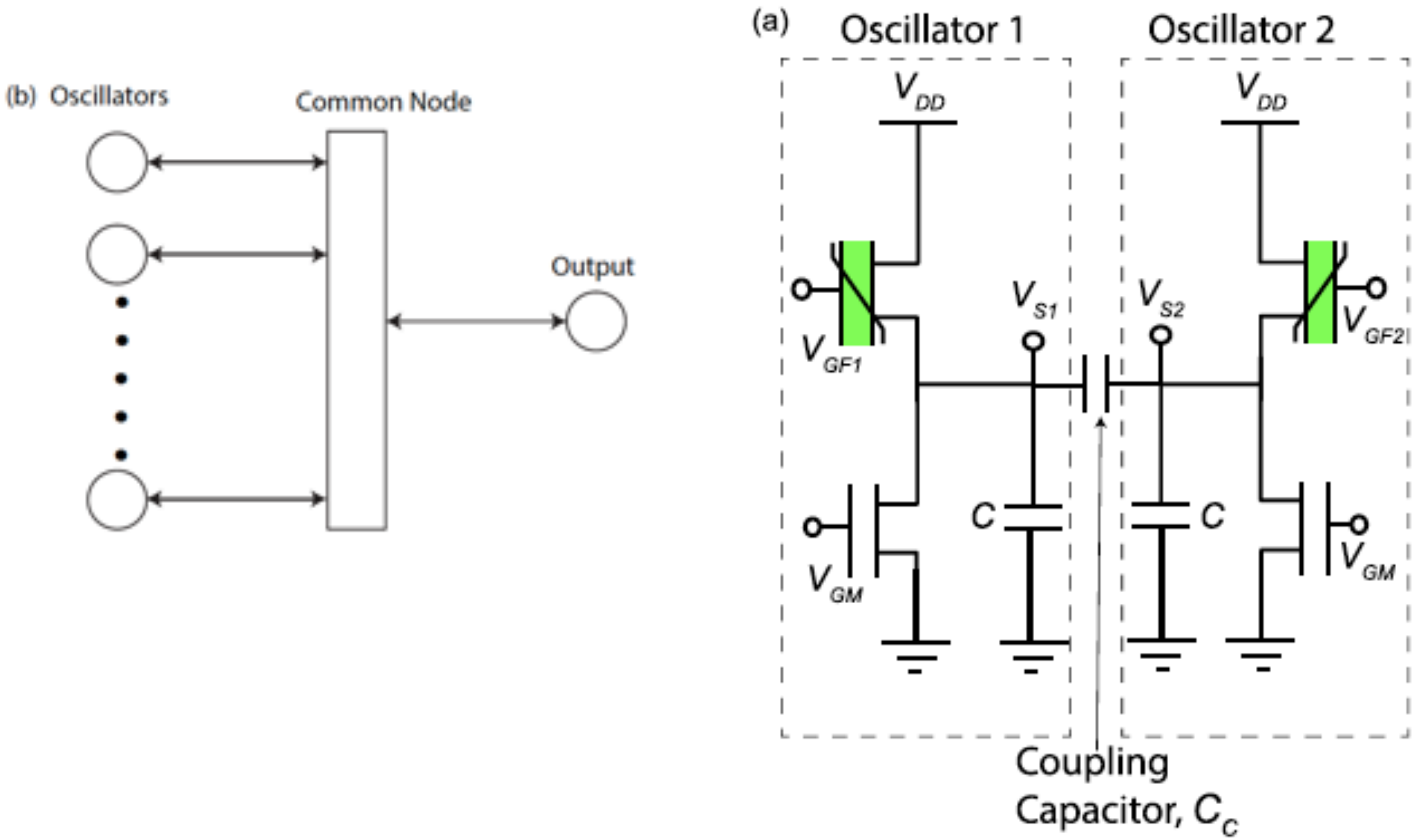
Ferroelectric Oscillator



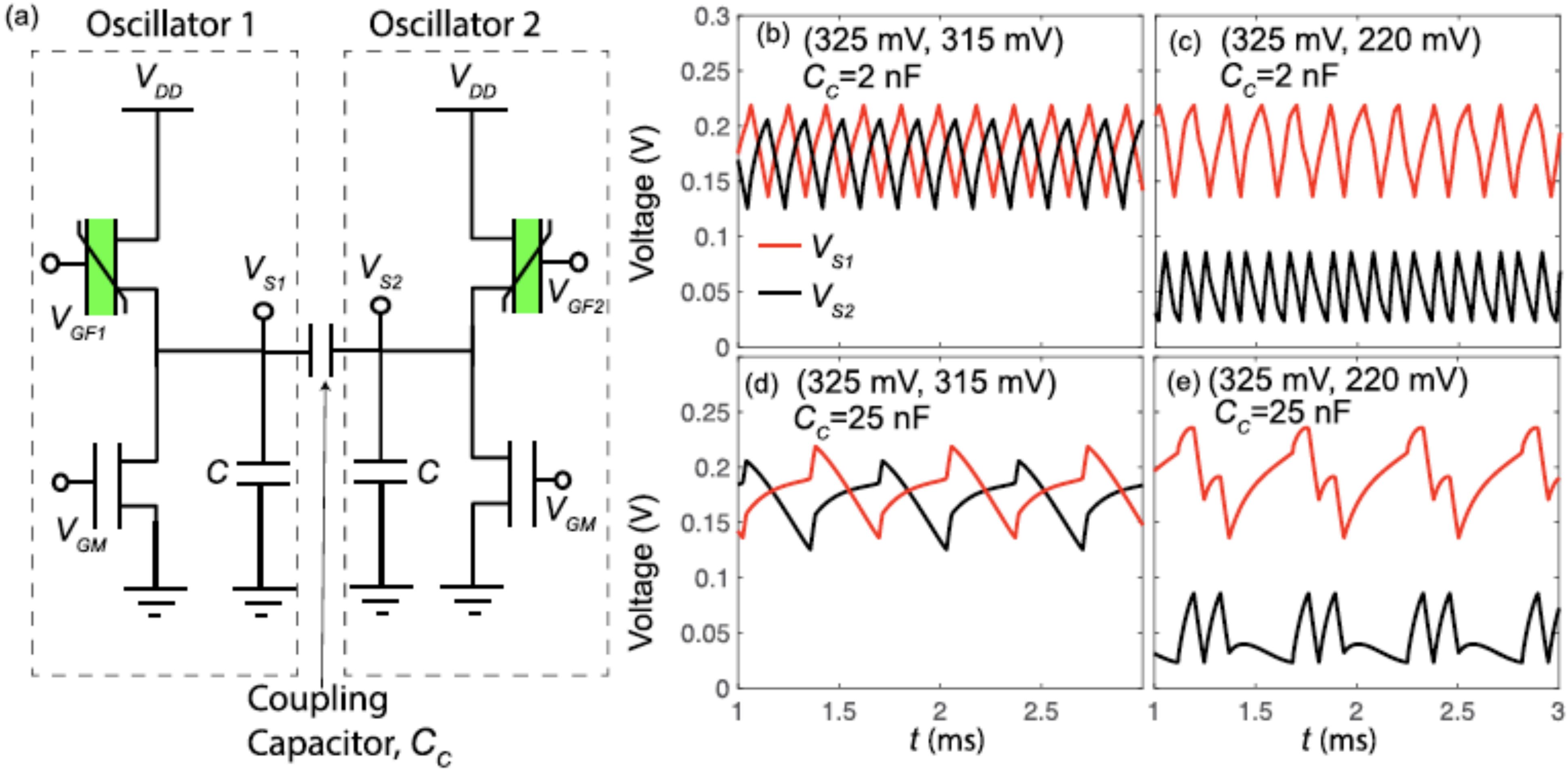


Georgia Tech

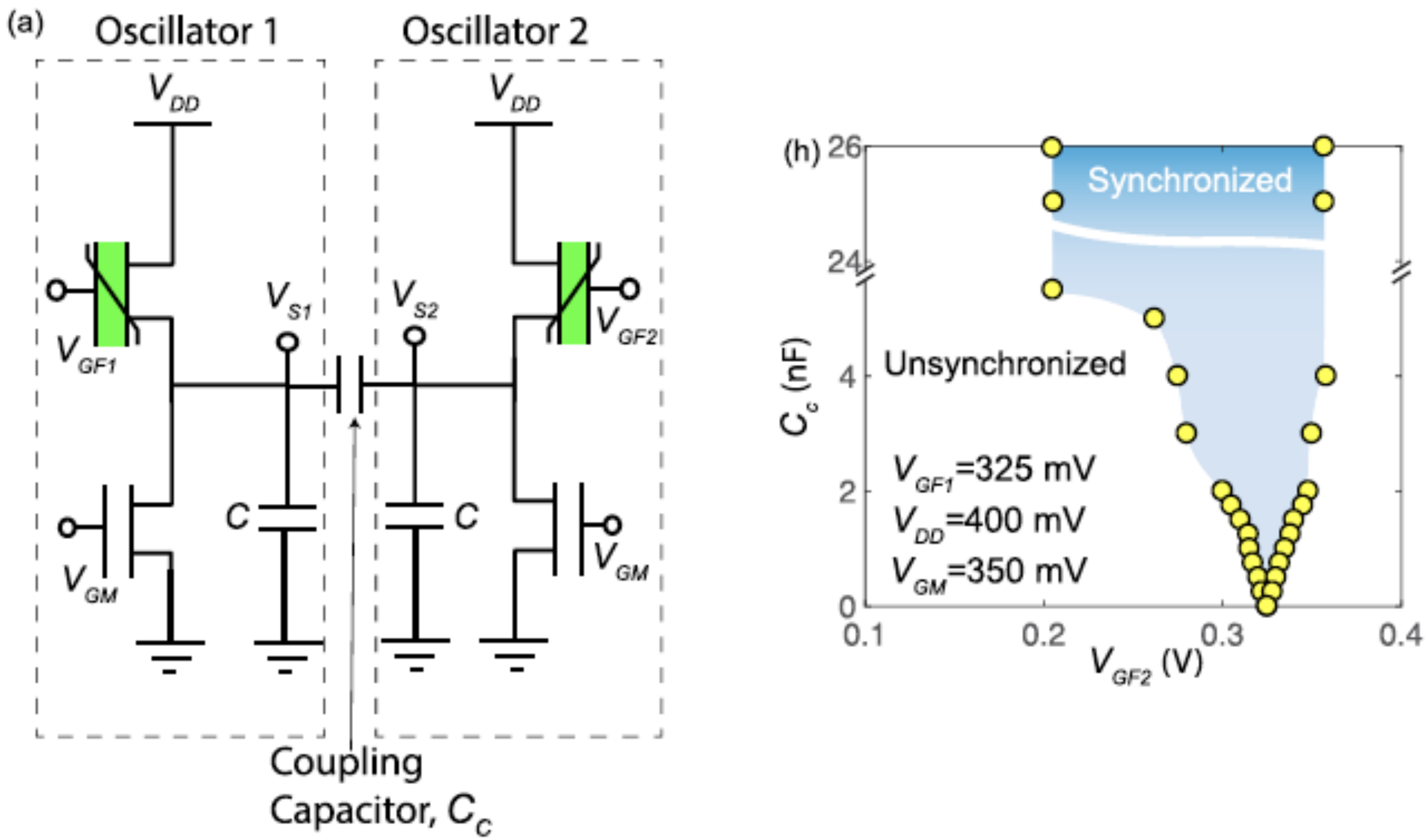
Coupled Ferroelectric Oscillator



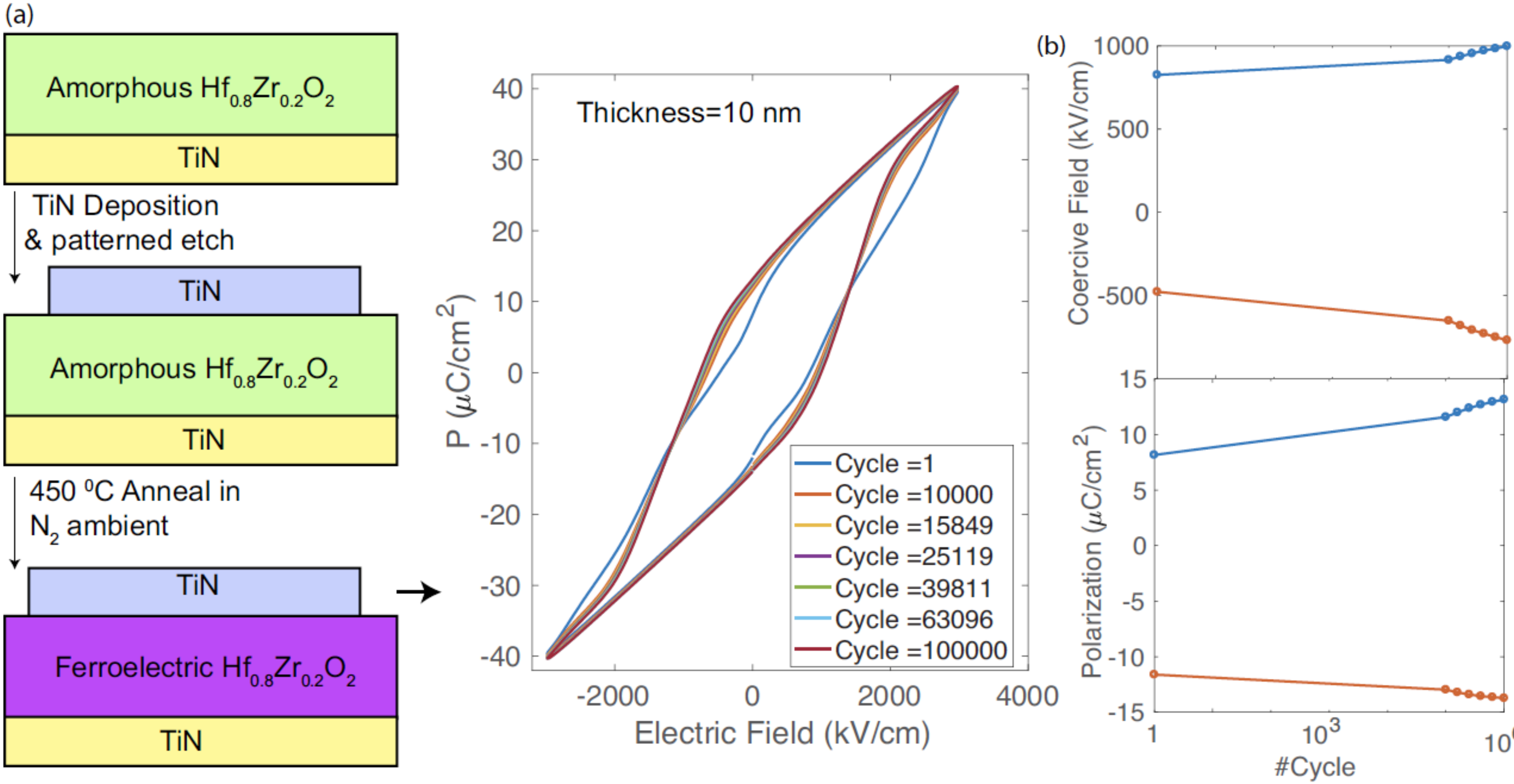
Coupled Ferroelectric Oscillator



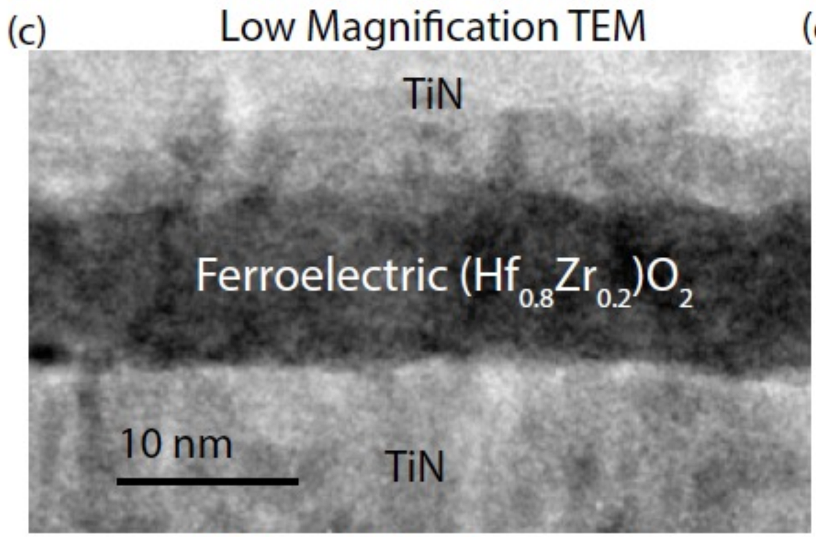
Coupled Ferroelectric Oscillator

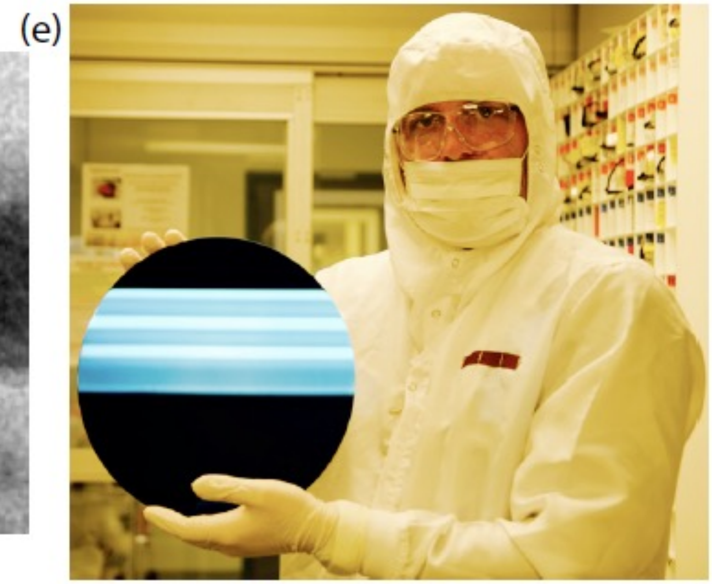


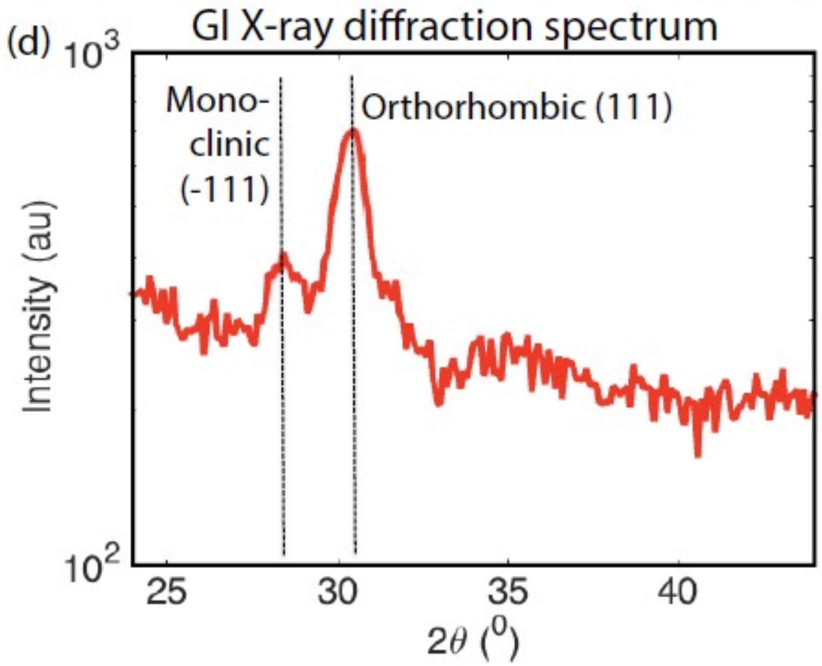
Ferroelectricity in $Hf_{0.8}Zr_{0.2}O_2$

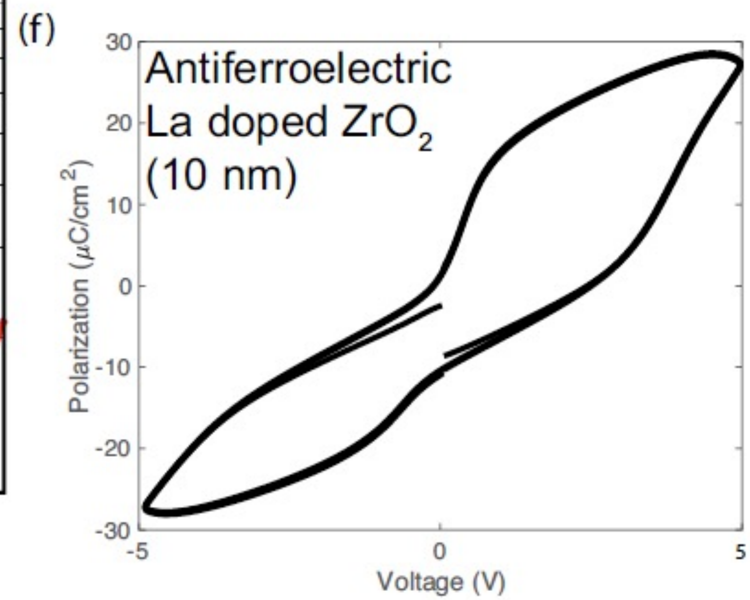


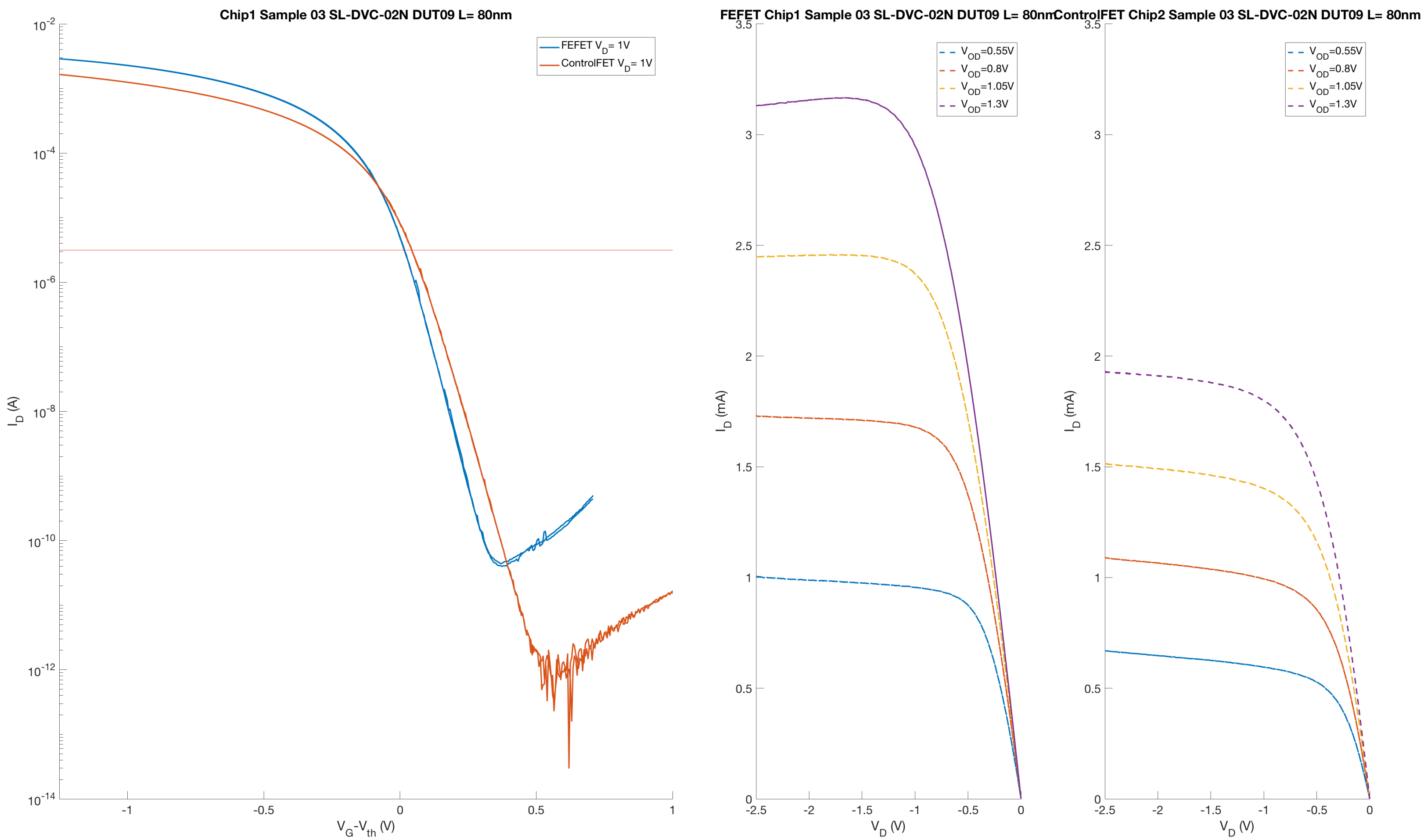
Anti-Ferroelectricity in Doped $Zr_{0.2}O_2$










Chip1 Sample 03 SL-DVC-02N DUT09 L= 80nm
FEFET V_D= 1V
ControlFET V_D= 1V
I_D (A)
V_G-V_{th} (V)
FEFET Chip1 Sample 03 SL-DVC-02N DUT09 L= 80nm
ControlFET Chip2 Sample 03 SL-DVC-02N DUT09 L= 80nm
V_{OD}=0.55V
V_{OD}=0.8V
V_{OD}=1.05V
V_{OD}=1.3V
I_D (mA)
V_D (V)

THANK YOU

QUESTIONS

&

COMMENTS

Summary

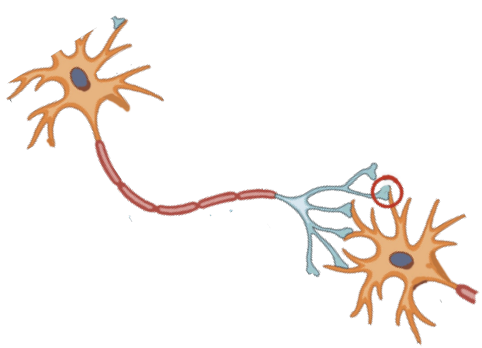
Dynamics of Brain's Functional Units: **Neurons and Synapse**

Dynamics of **Memory Materials & Devices**

New Computational Capabilities

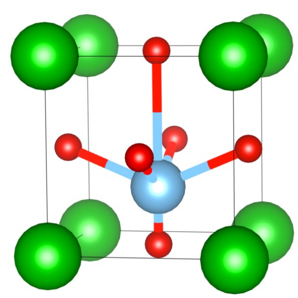
Short Term Plasticity and Long Term Potentiation

- Theoretical Framework



Ferroelectric Memory:

- Landau Dynamics
- Experimental realization



Possible Application in Pattern Memorization, Recognition