Ferroelectrics for Brain-Inspired Computing

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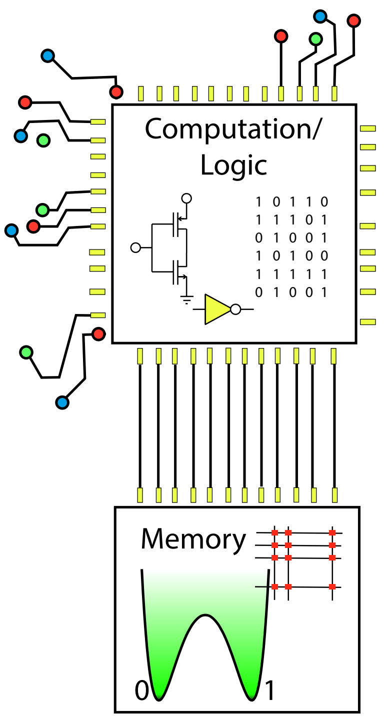
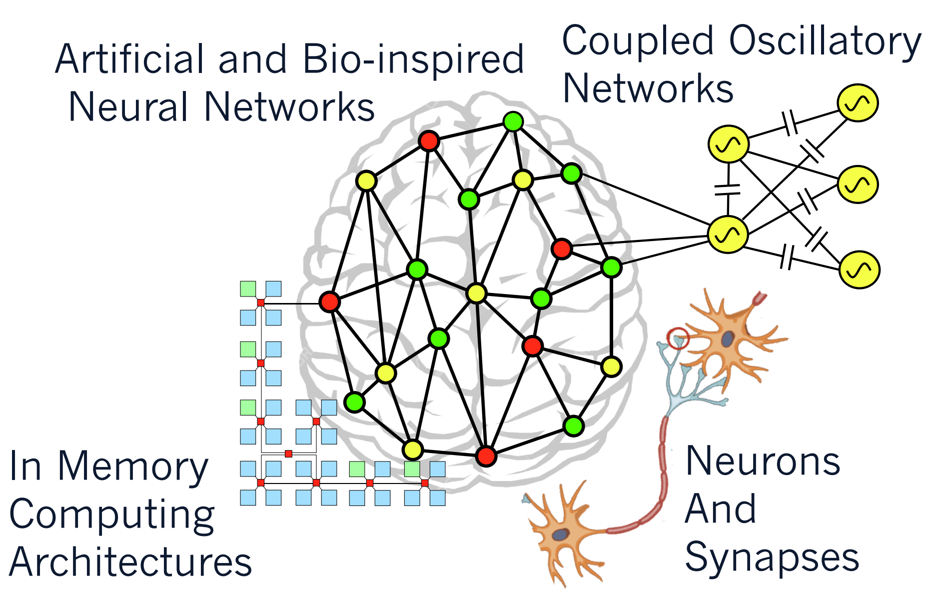
Emerging paradigms in computing and electronics

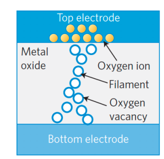
von Neuman Architecture



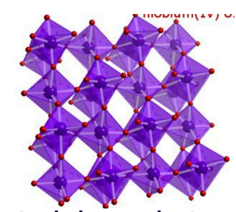
With the rise of data-intensive computing applications, we need **non-von Neumann** and **brain inspired/neuromorphic** computing models and architectures.



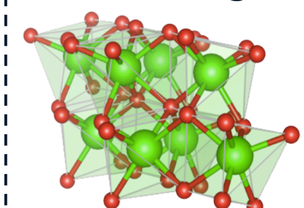
Emerging Materials and Devices



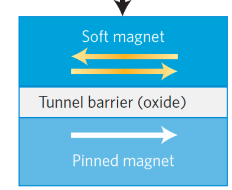
Resistive Switching



Metal-Insulator Transition



Ferroelectricity



Spintronics

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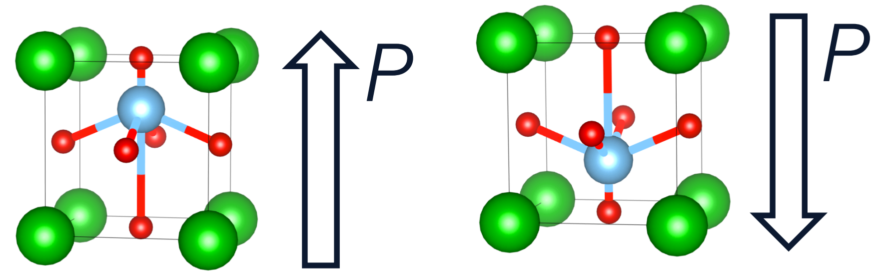
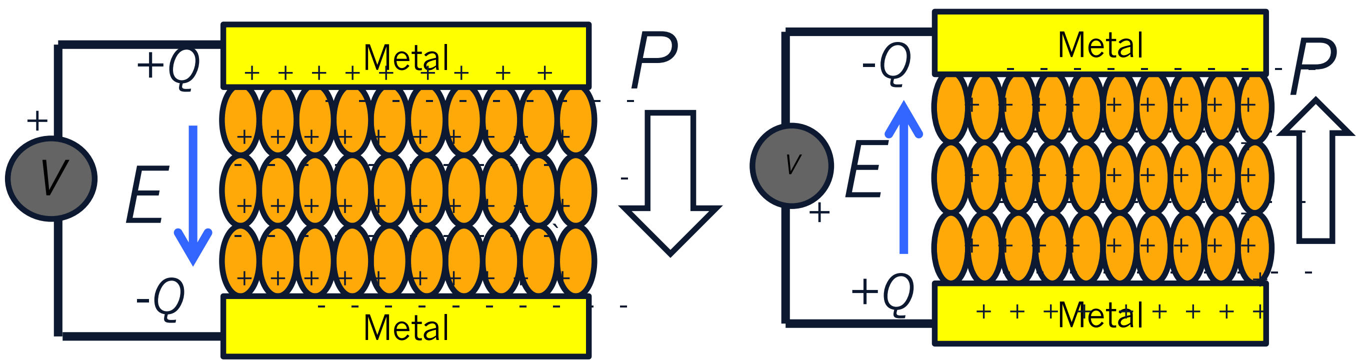
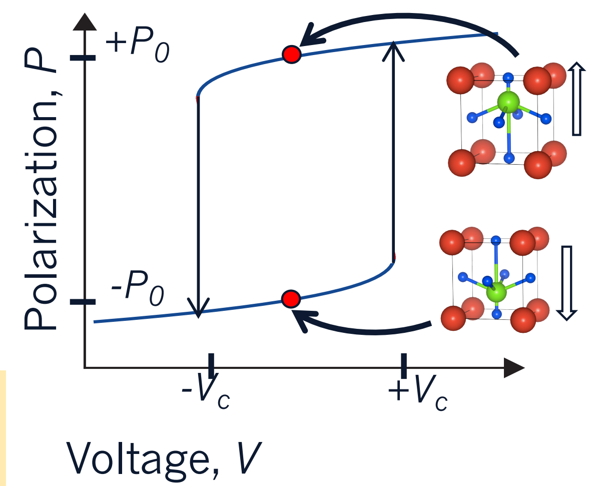
Ferroelectric Oxides

Classical Ferroelectric
$PbTiO_3$, $BaTiO_3$ etc.
Emerging CMOS compatible
Ferroelectrics:
Doped HfO_2





A ferroelectric is an insulator with a spontaneous polarization, which can be switched by an above coercive voltage .



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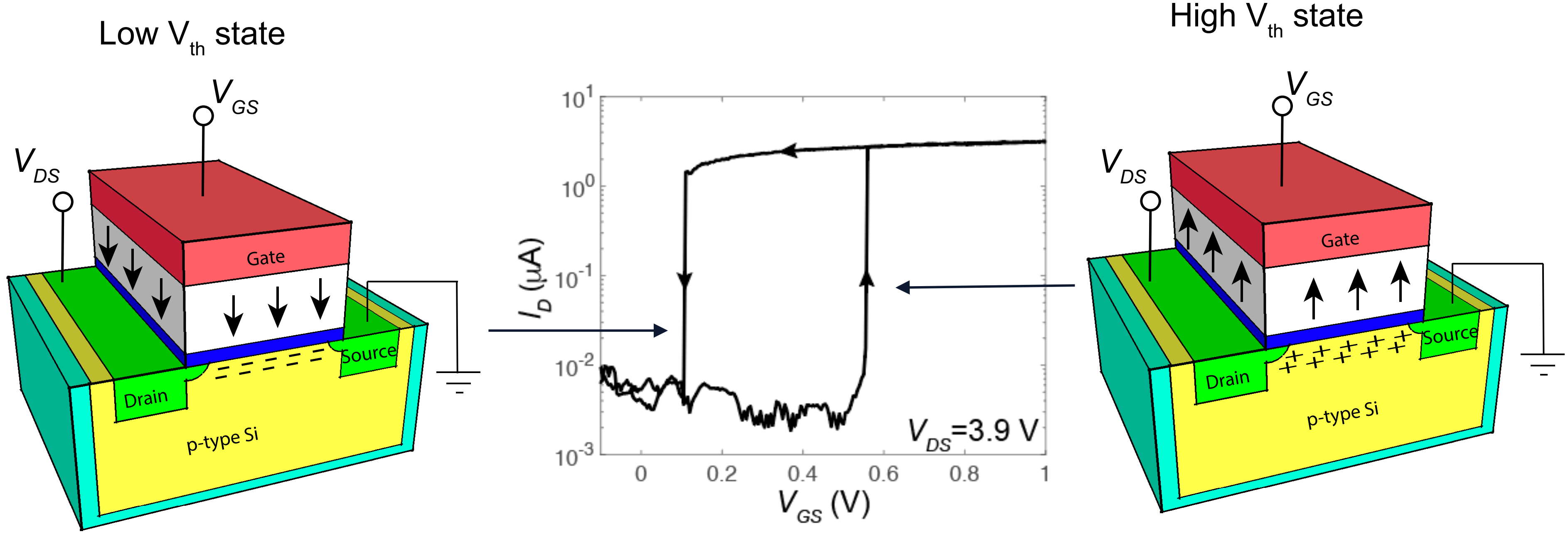
Ferroelectric Field-Effect Transistors

Ferrroelectric Transistors (FEFET): Gate oxide stack includes a FE oxide



A ferroelectric transistor is a hysteretic device where the data is encoded in ferroelectric polarization.

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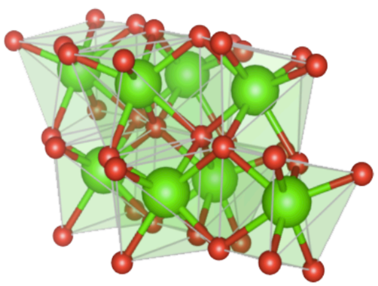
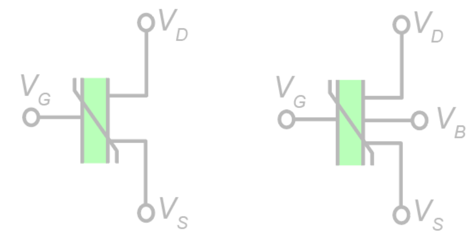
What is so great about Ferroelectric Transistors?

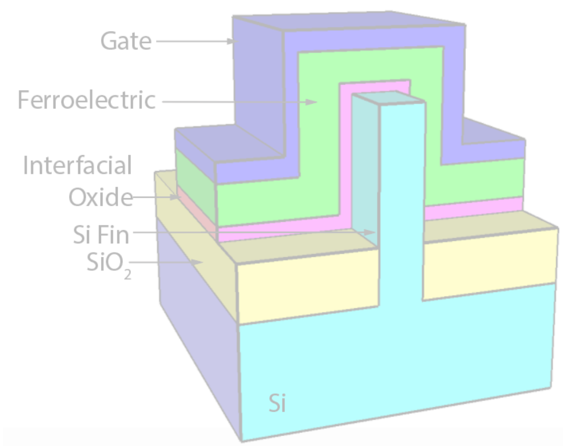
Ferroelectric Oxides



- Hysteresis
- Non-volatile
- Plasticity
- Stochasticity

Ferroelectric FET





- Gain
- Circuit Configurability

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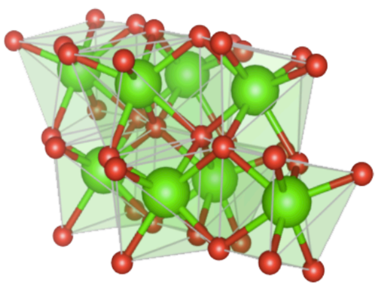
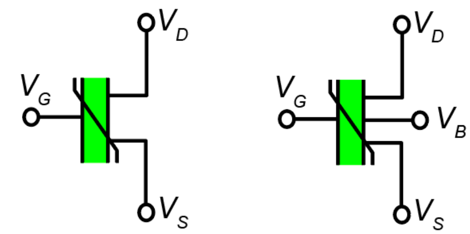
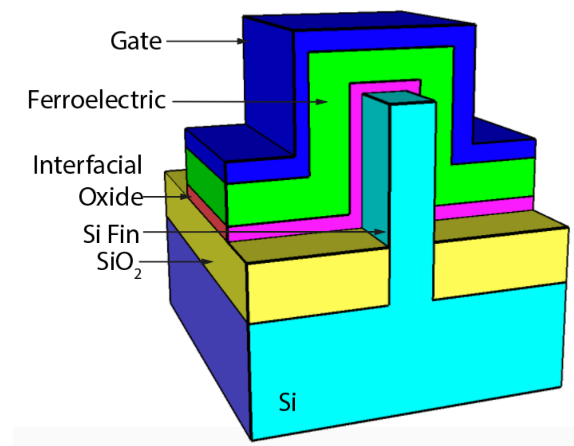
What is so great about Ferroelectric Transistors?

Ferroelectric Oxides



Ferroelectric FET





- Hysteresis
- Non-volatile
- Plasticity
- Gain
- Stochasticity
- Circuit Configurability

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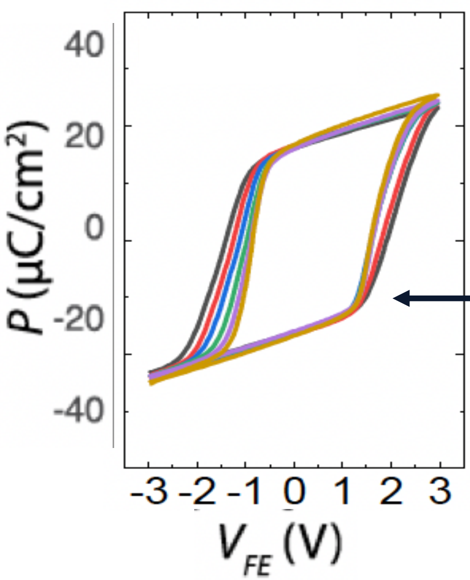
Switching dynamics in ferroelectric: Abrupt vs. diffuse

Ferroelectric-1

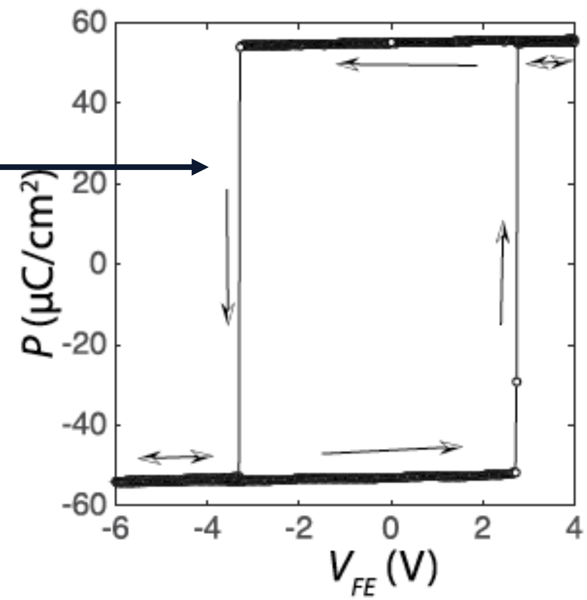


Switching Transition

Abrupt

Diffuse

Ferroelectric-2



Functionality
Abrupt: Neuron
Diffuse: Synapse

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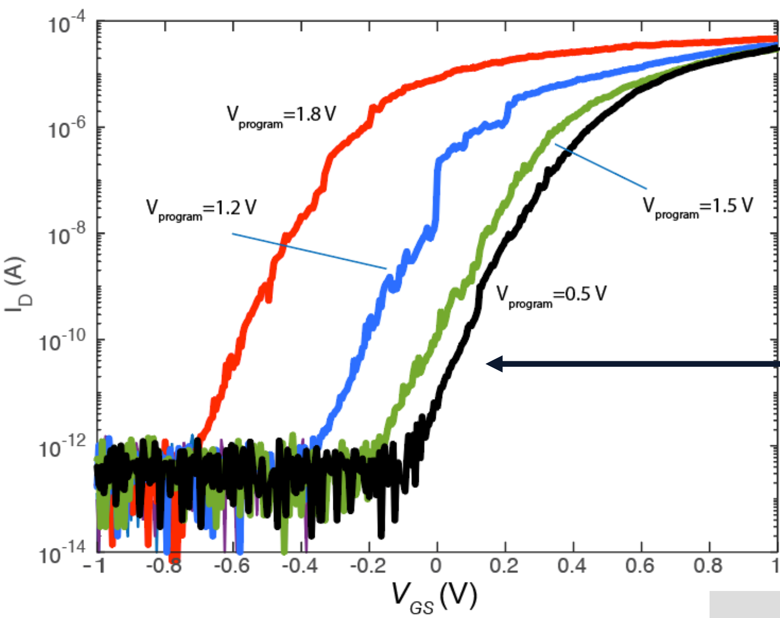
Switching dynamics in ferroelectric transistor: Abrupt vs. diffuse

Ferroelectric FET for Synapse

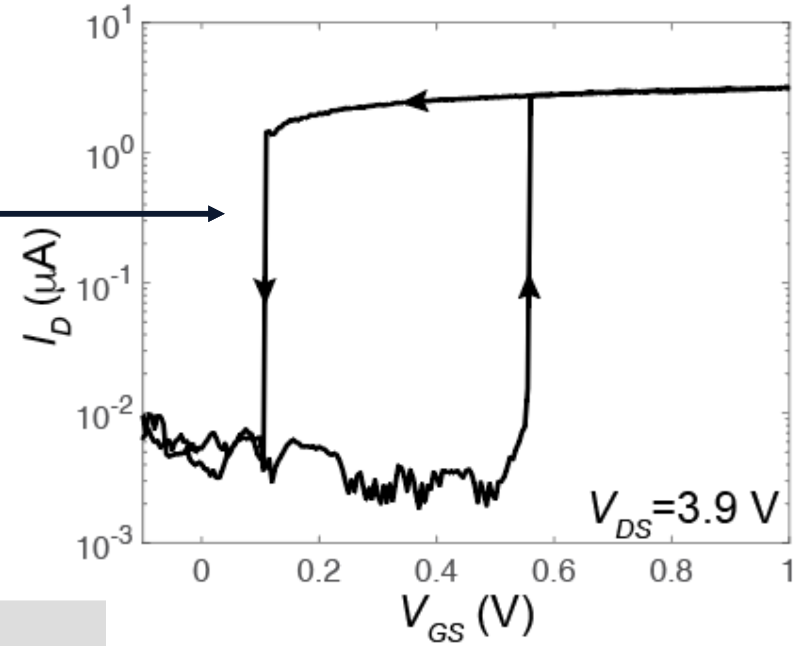


Switching Transitions

Abrupt

Diffuse

Ferroelectric FET for Neuron



Functionality
Abrupt: Neuron
Diffuse: Synapse

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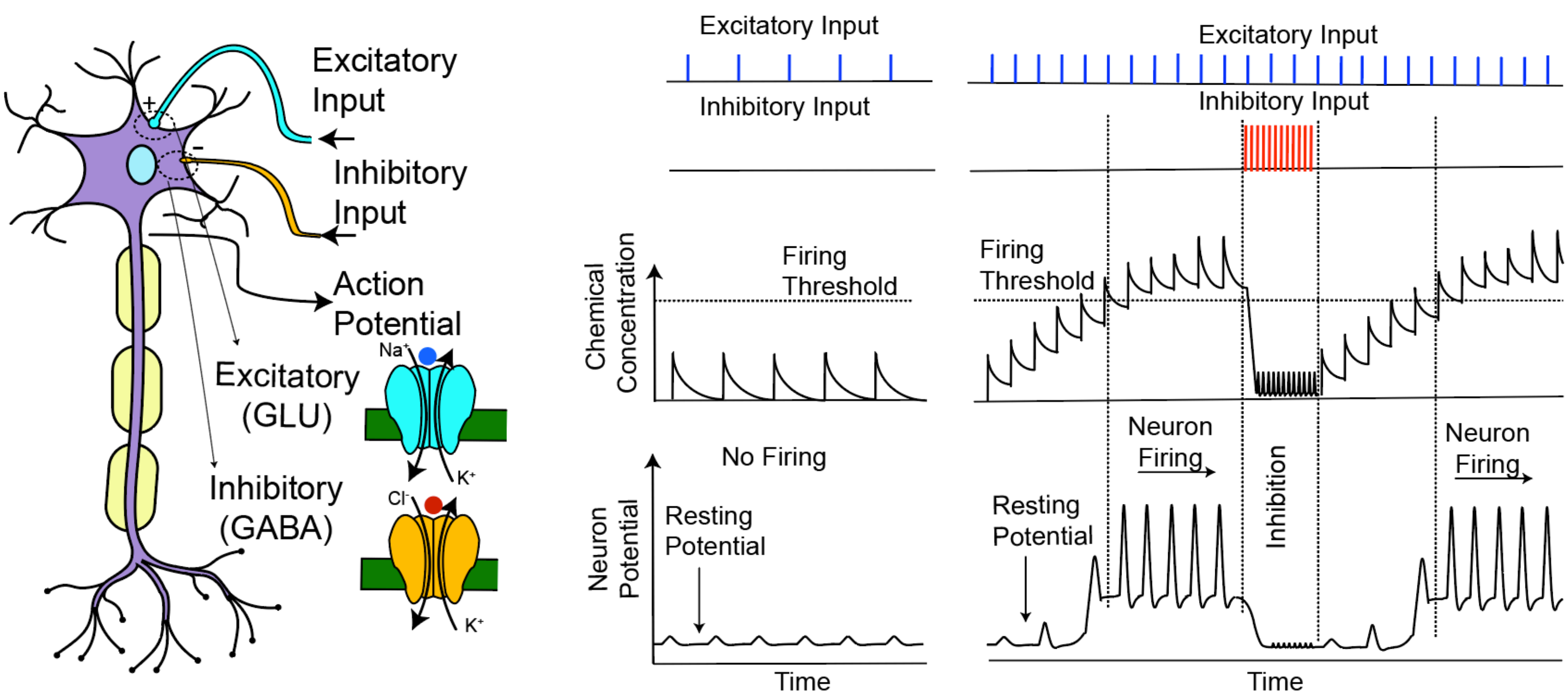
A Biological Neuron



Biology: Inhibition required for regulation in activation of excitatory neurons; homeostasis.
Bio-inspired computing: High accuracy in unsupervised learning.

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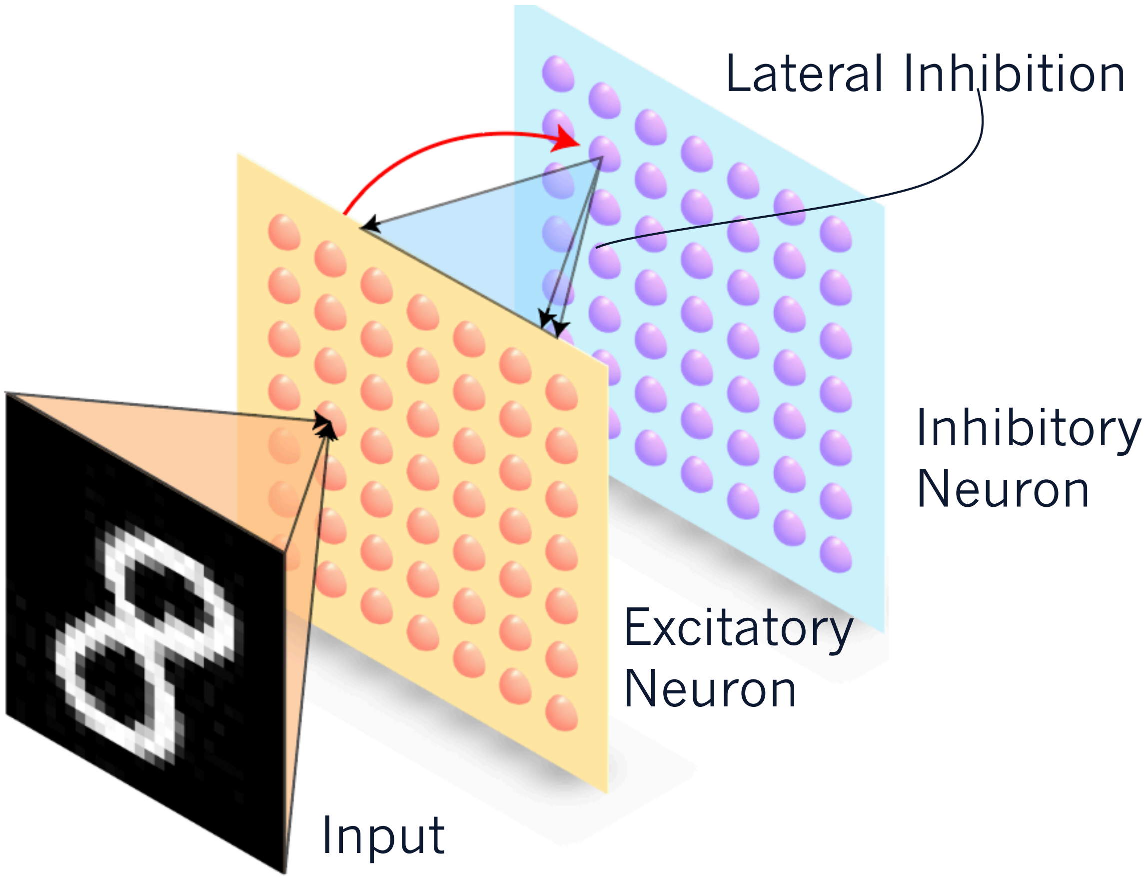
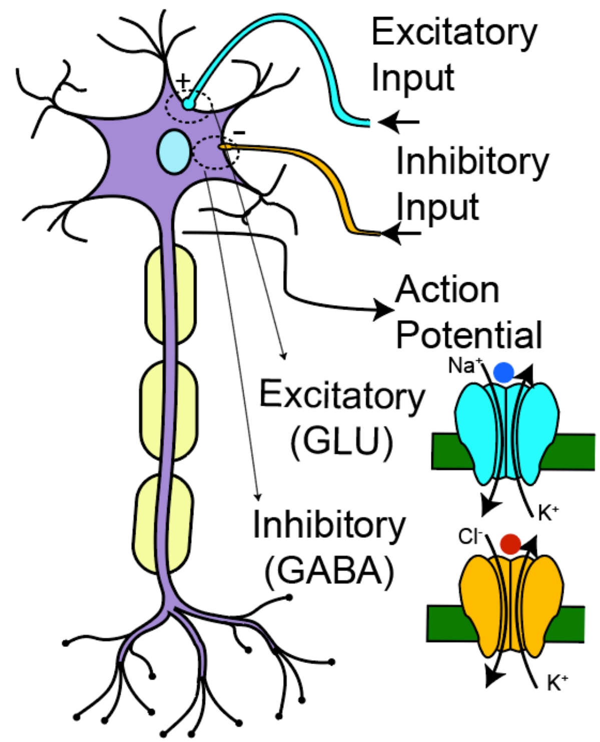
Spiking Neural Network: The Role of Inhibition



Deihl & Cook, Frontiers Comp. Neurosci. 9, 99 (2015)



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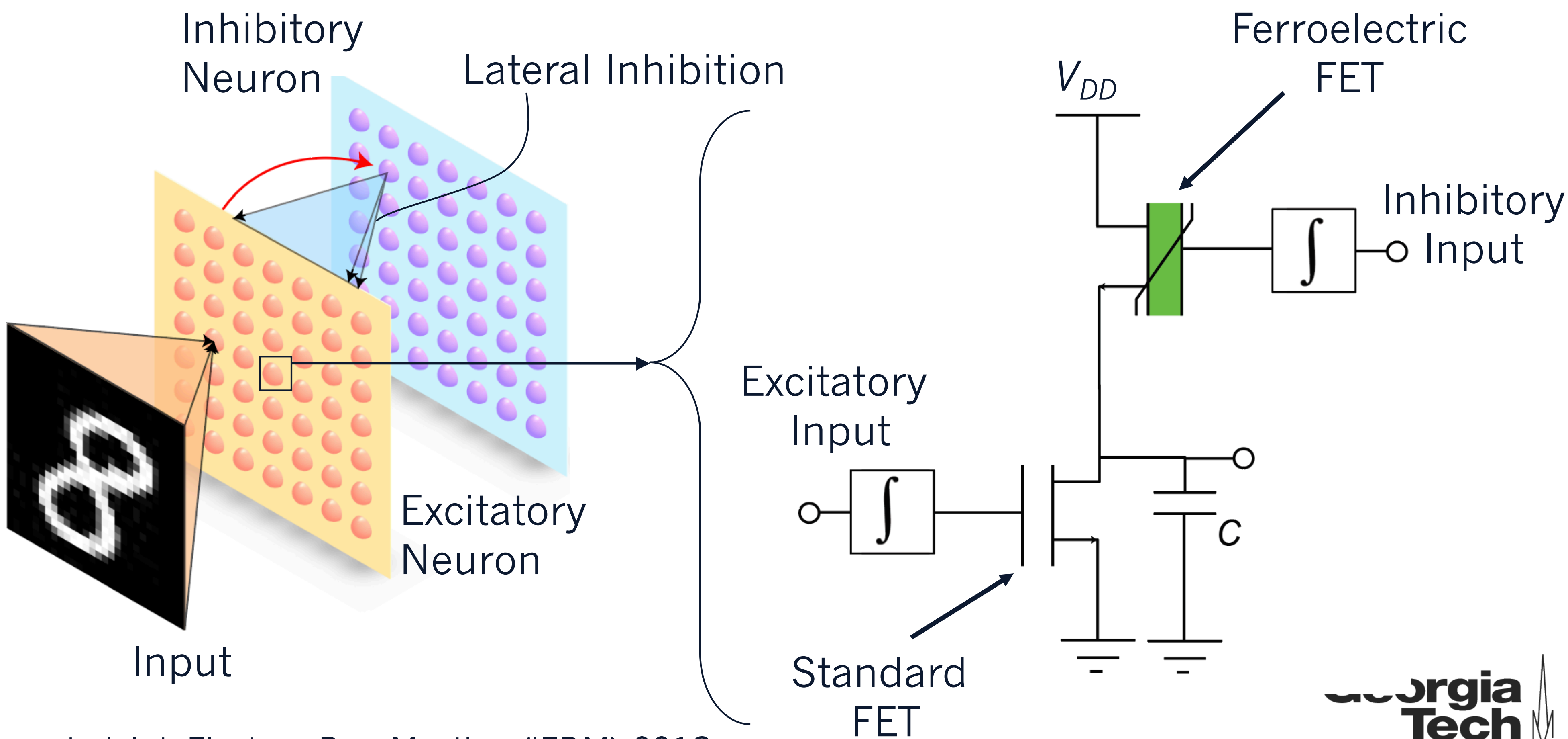
Ferroelectric Neuron with excitatory and **inhibitory** connection



Wang et al. Int. Electron Dev. Meeting (IEDM) 2018.

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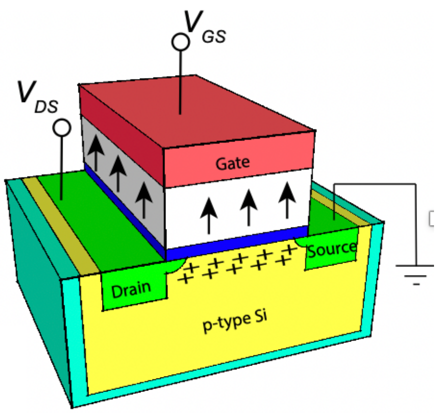
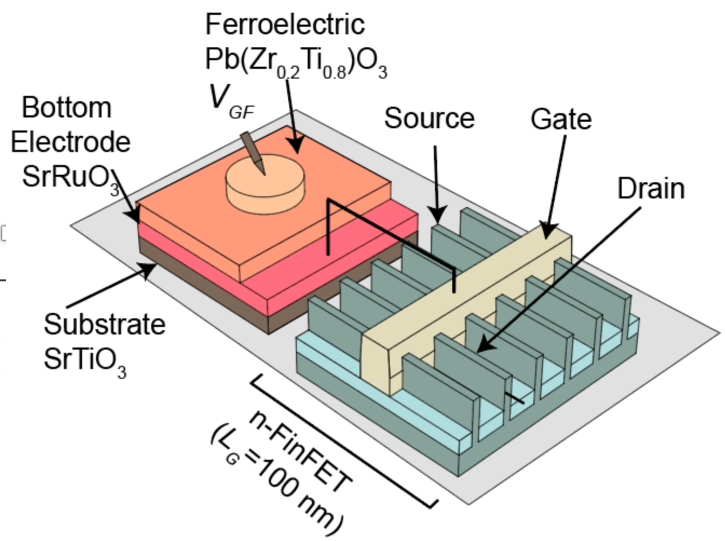
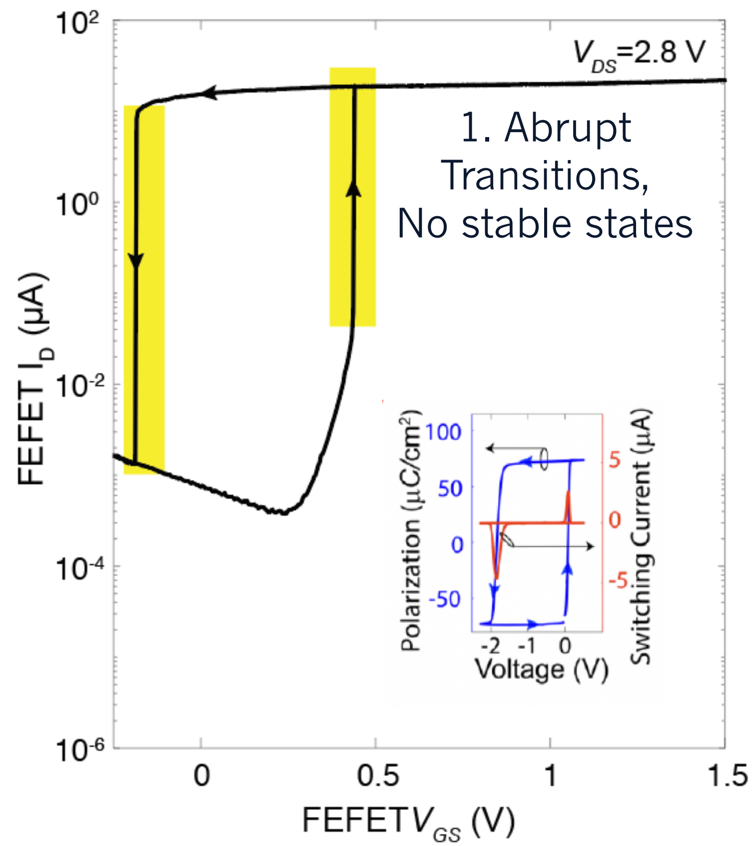
What Ferroelectric Features enables the **Neuron Inhibition** Functionality?

Ferroelectric Transistor



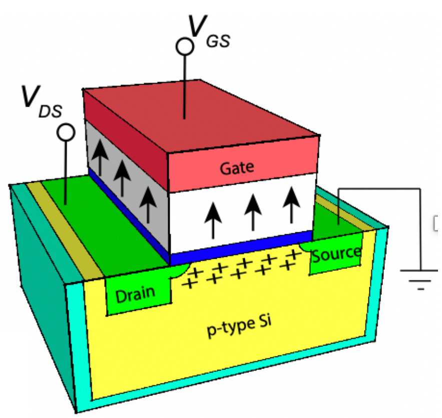


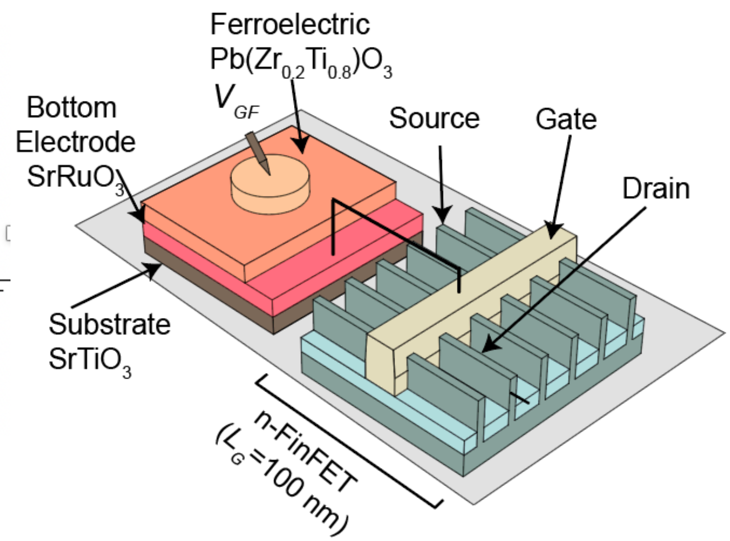


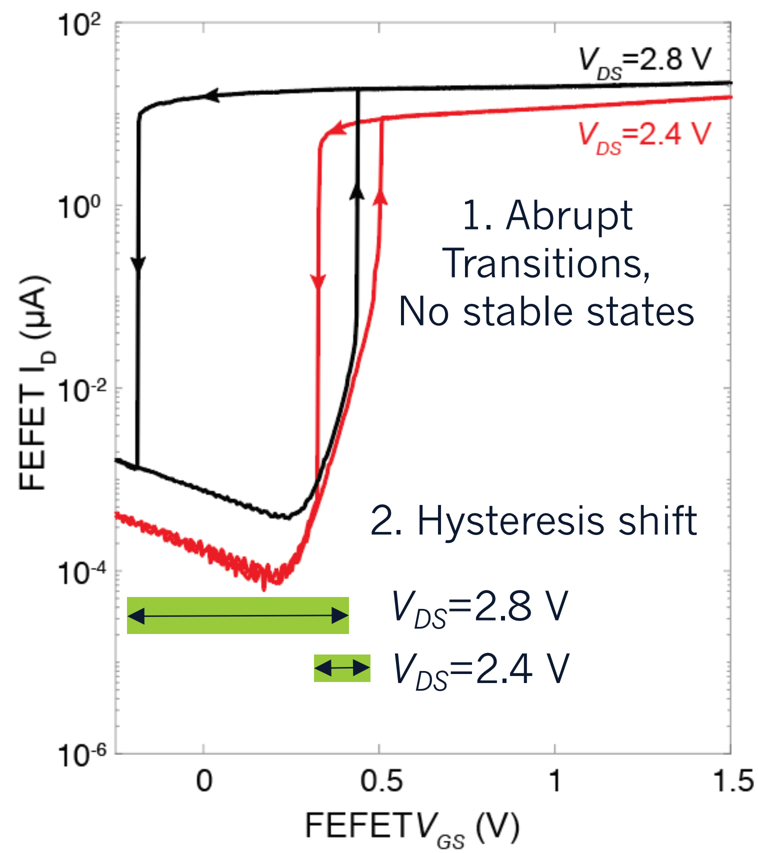
Abrupt transitions in FEFET are the key!

What Ferroelectric Features enables the **Neuron Inhibition** Functionality?

Ferroelectric Transistor

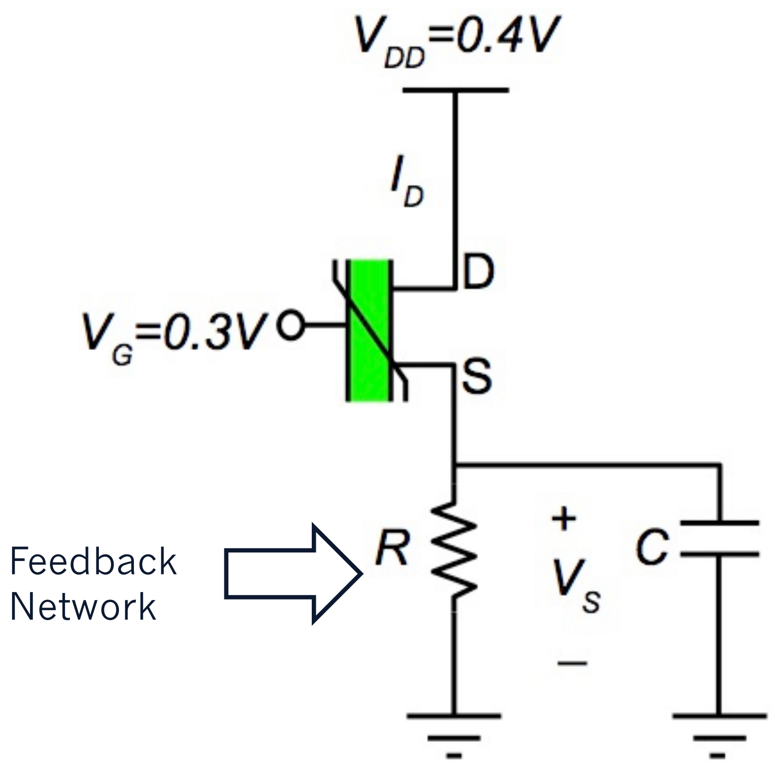


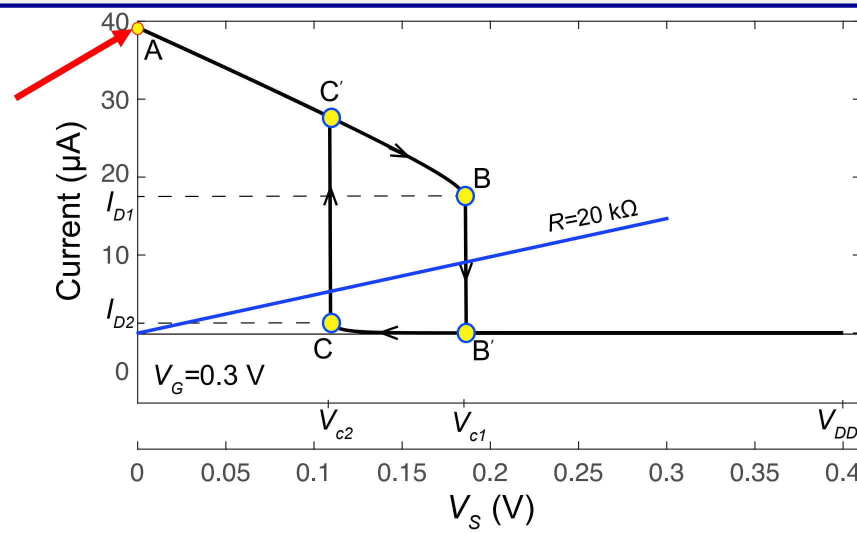


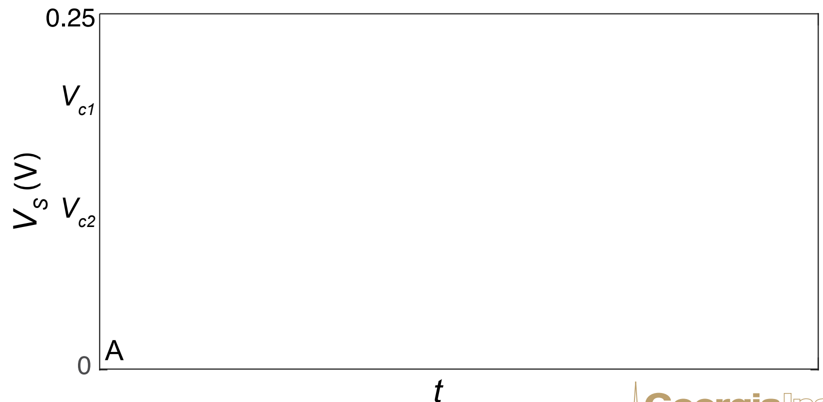


Abrupt transitions in FEFET are the key!

DYNAMICS OF FERROELECTRIC OSCILLATOR







FEFET is at point A initially

Z. Wang et al. *IEEE Electron Device Lett.* vol. 38, no. 11, pp. 1614–1617, 2017.

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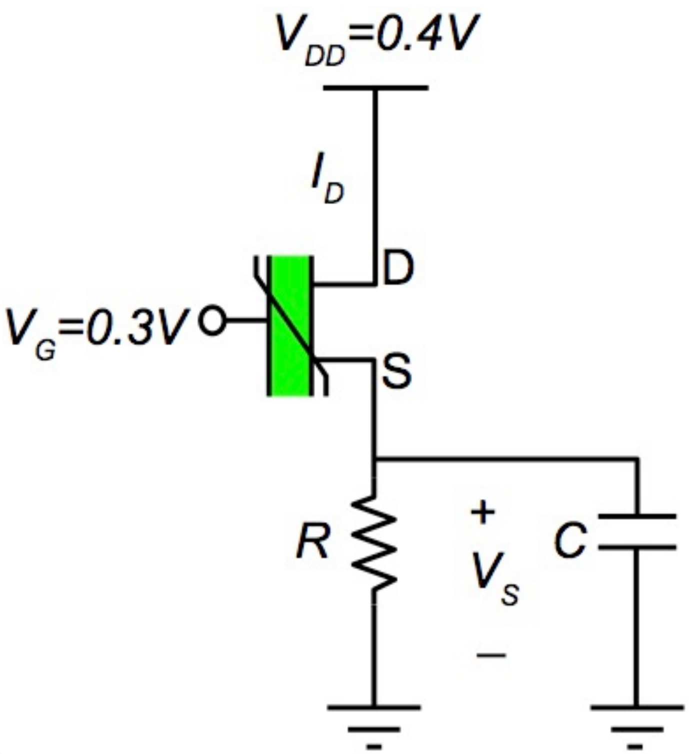

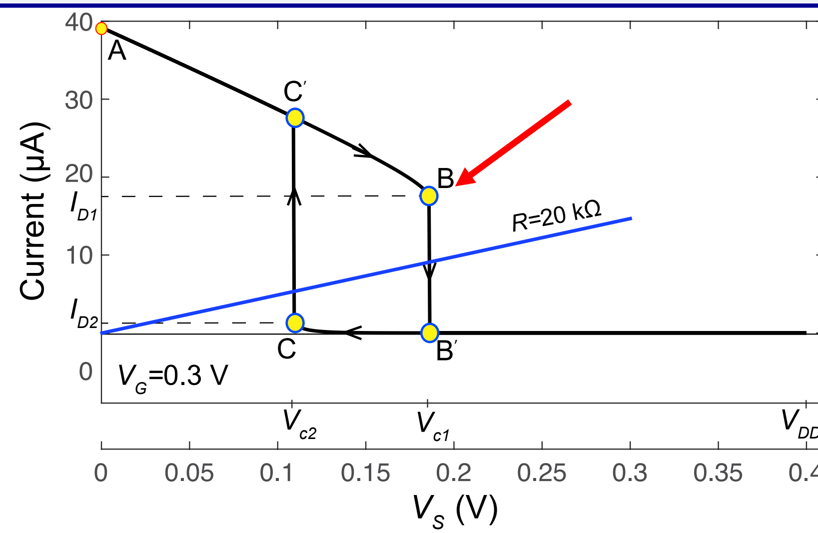

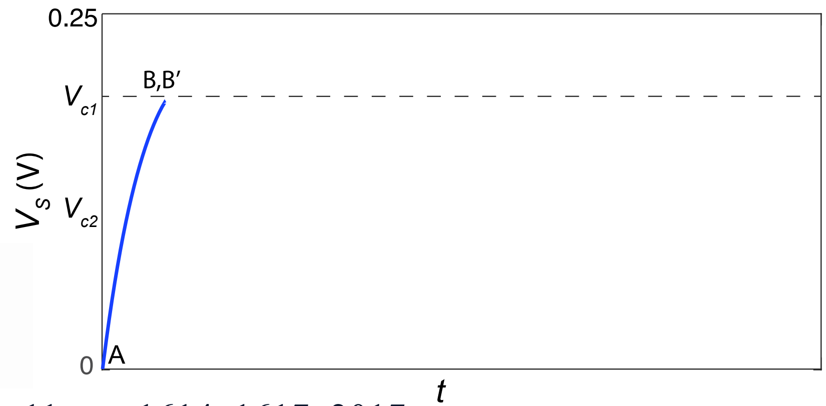

No stable states in the abrupt transition region between B and B’

Z. Wang et al. *IEEE Electron Device Lett.* vol. 38, no. 11, pp. 1614–1617, 2017.

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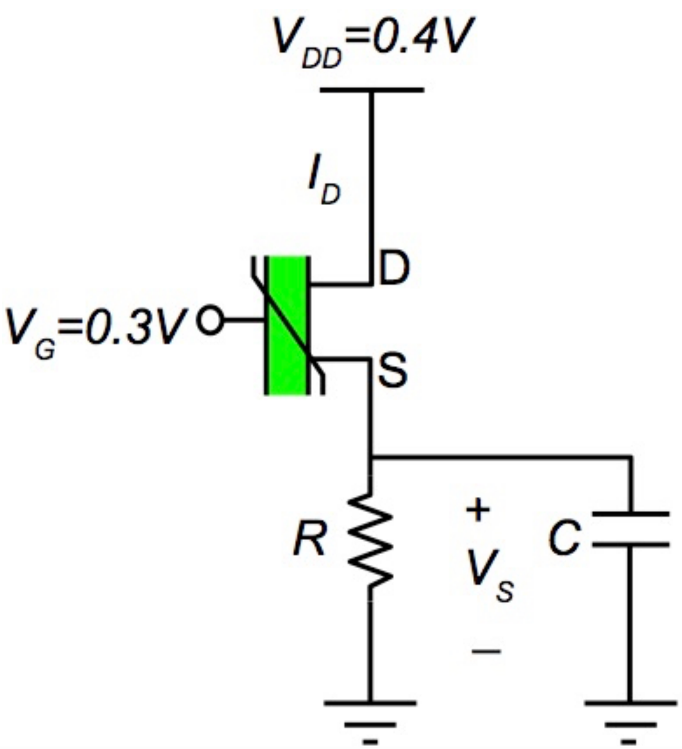

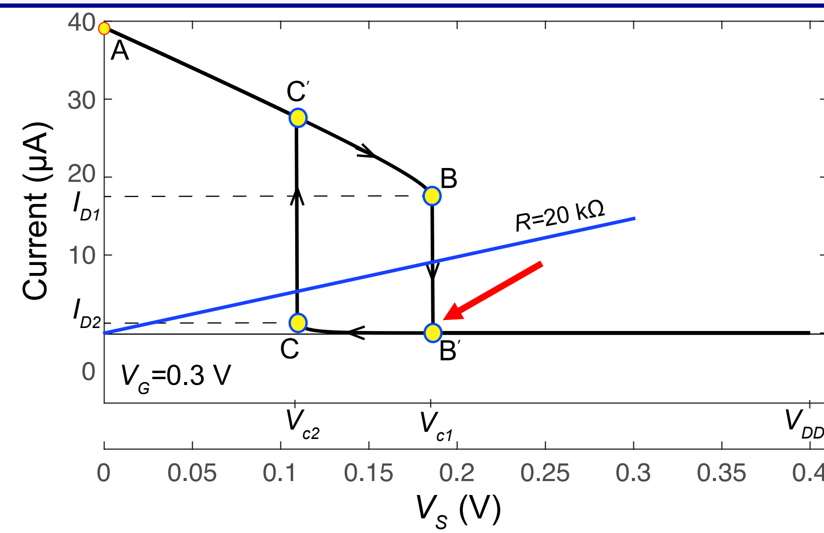

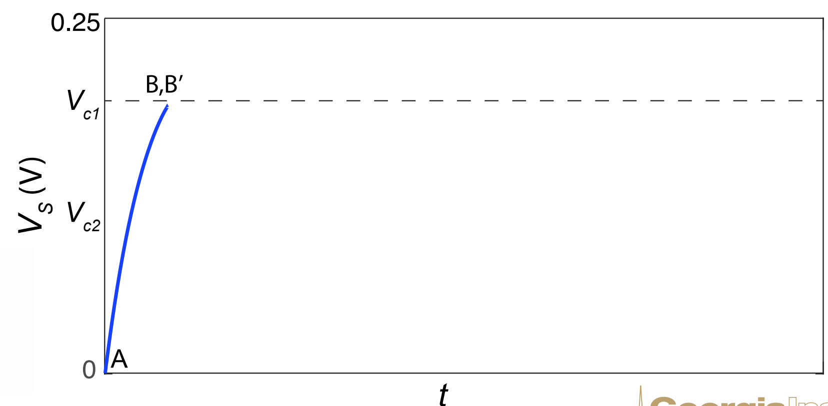

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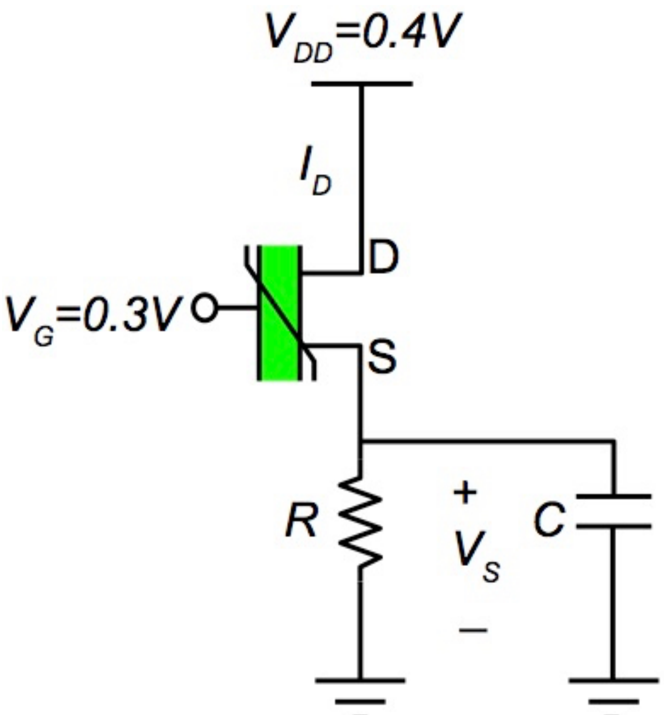

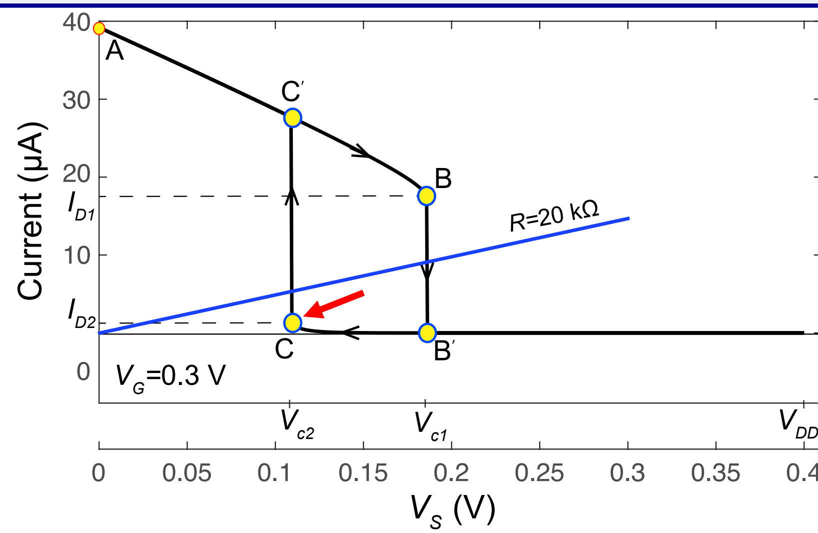

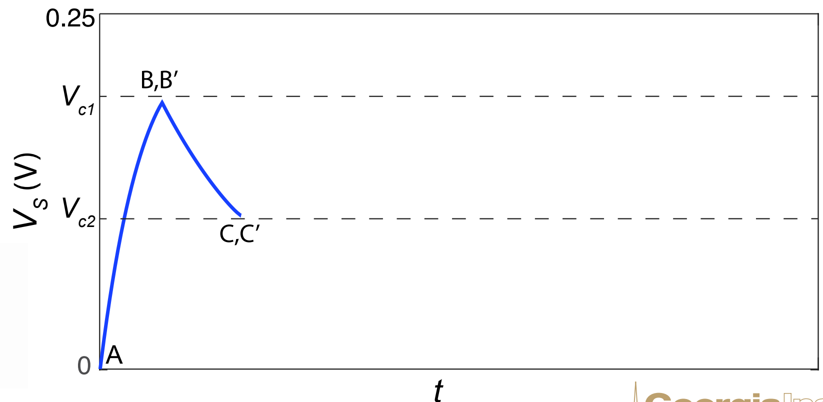

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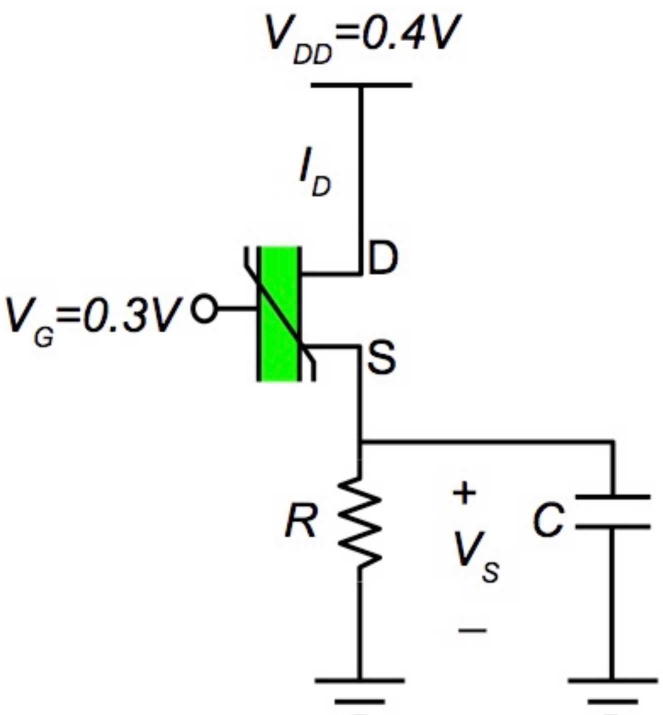

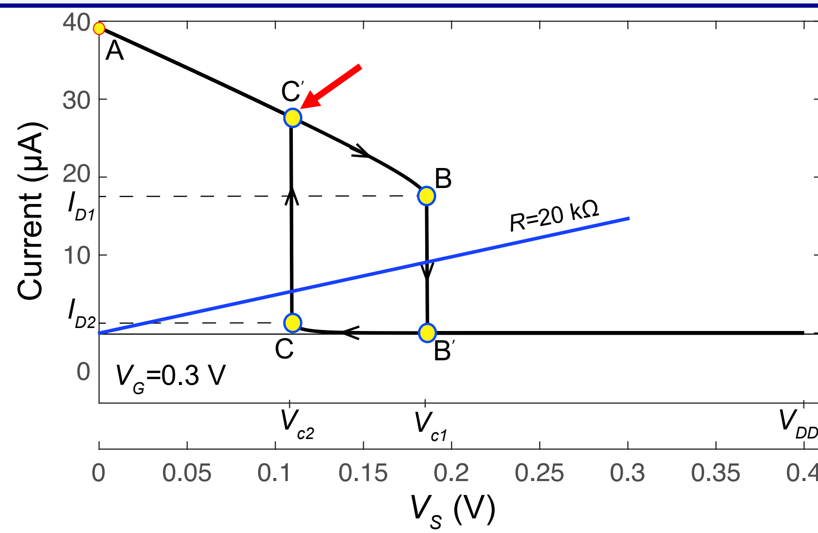

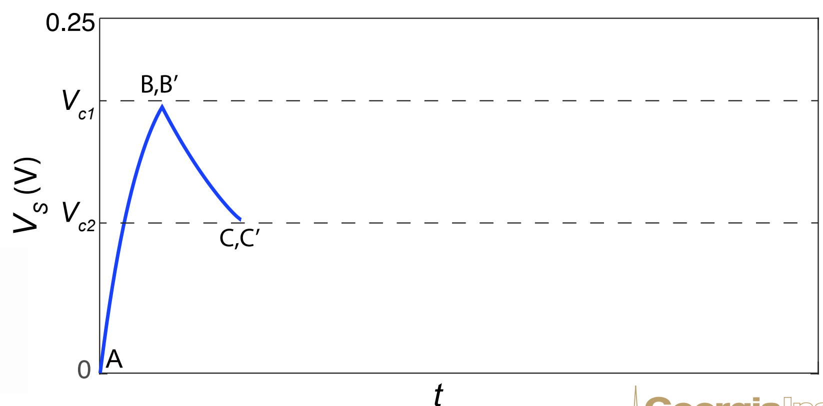

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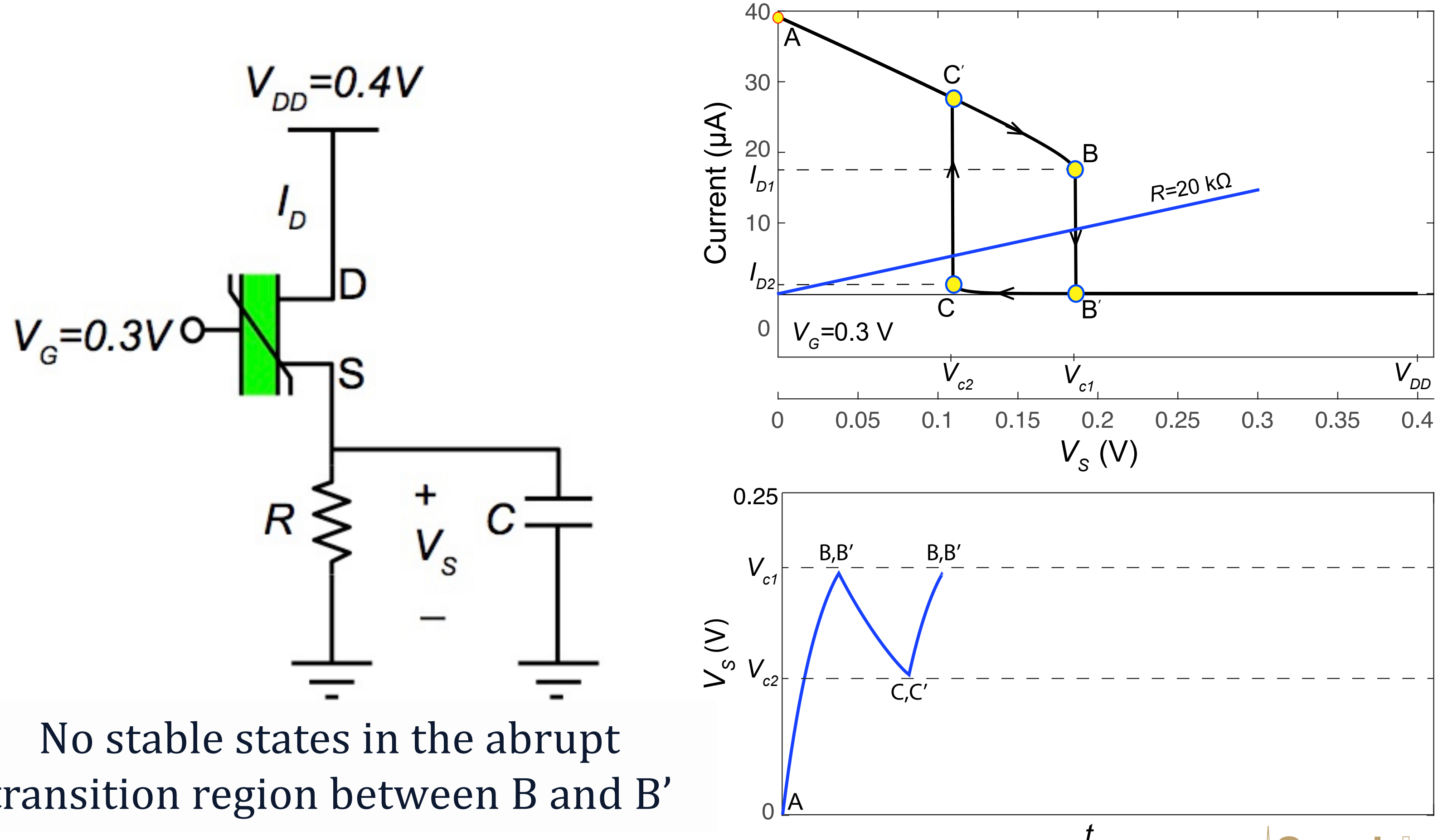

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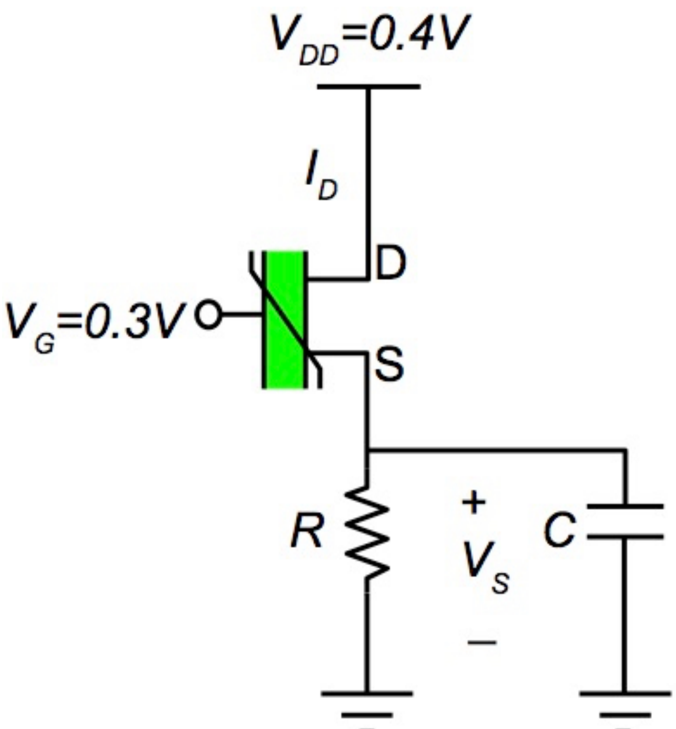

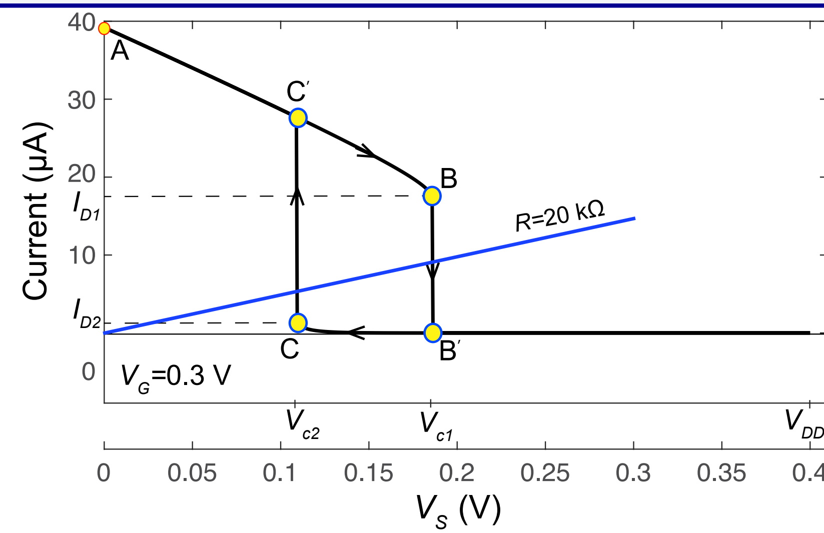

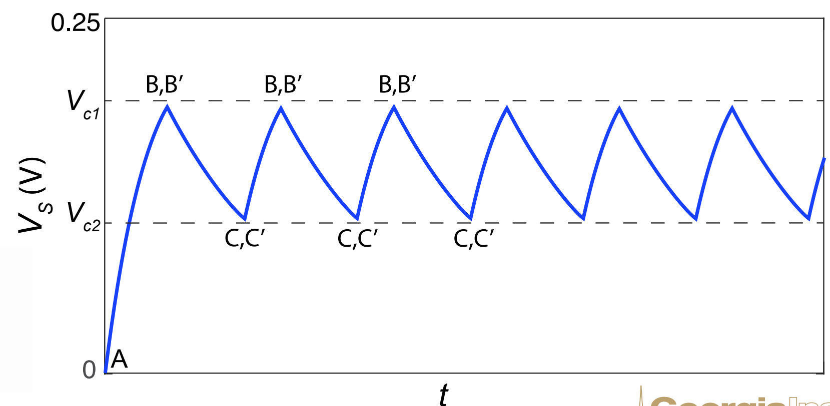

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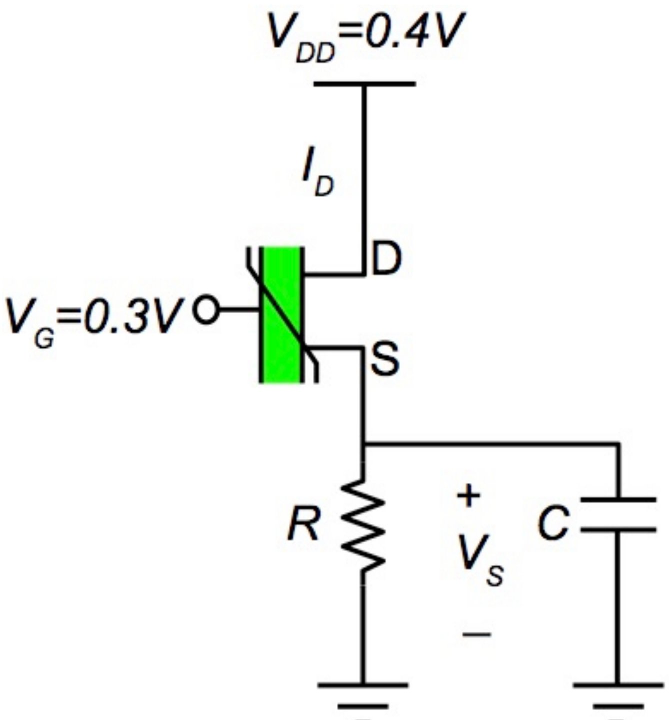
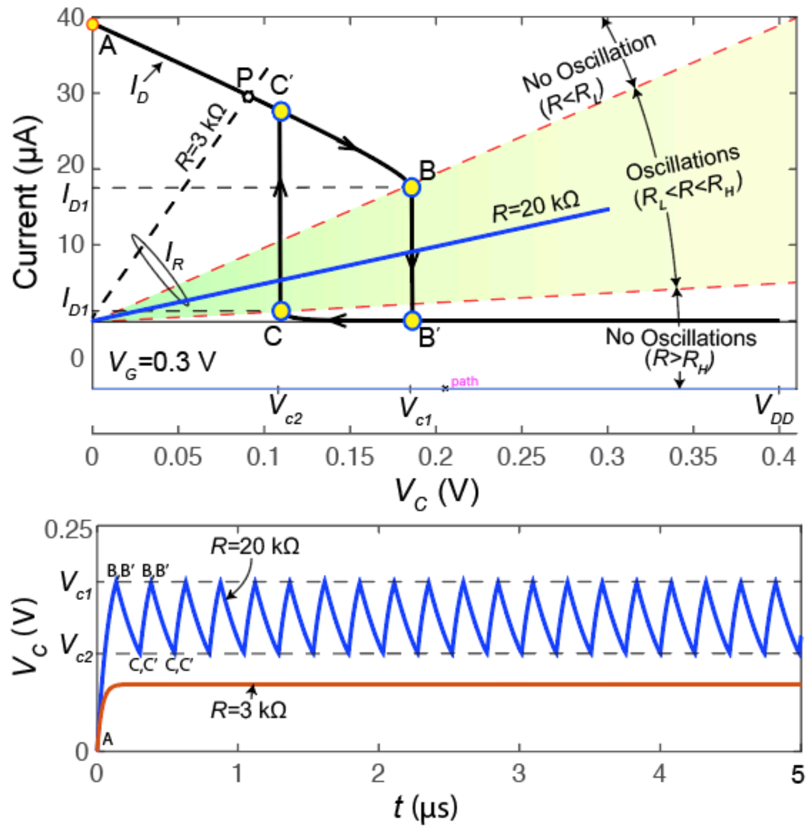
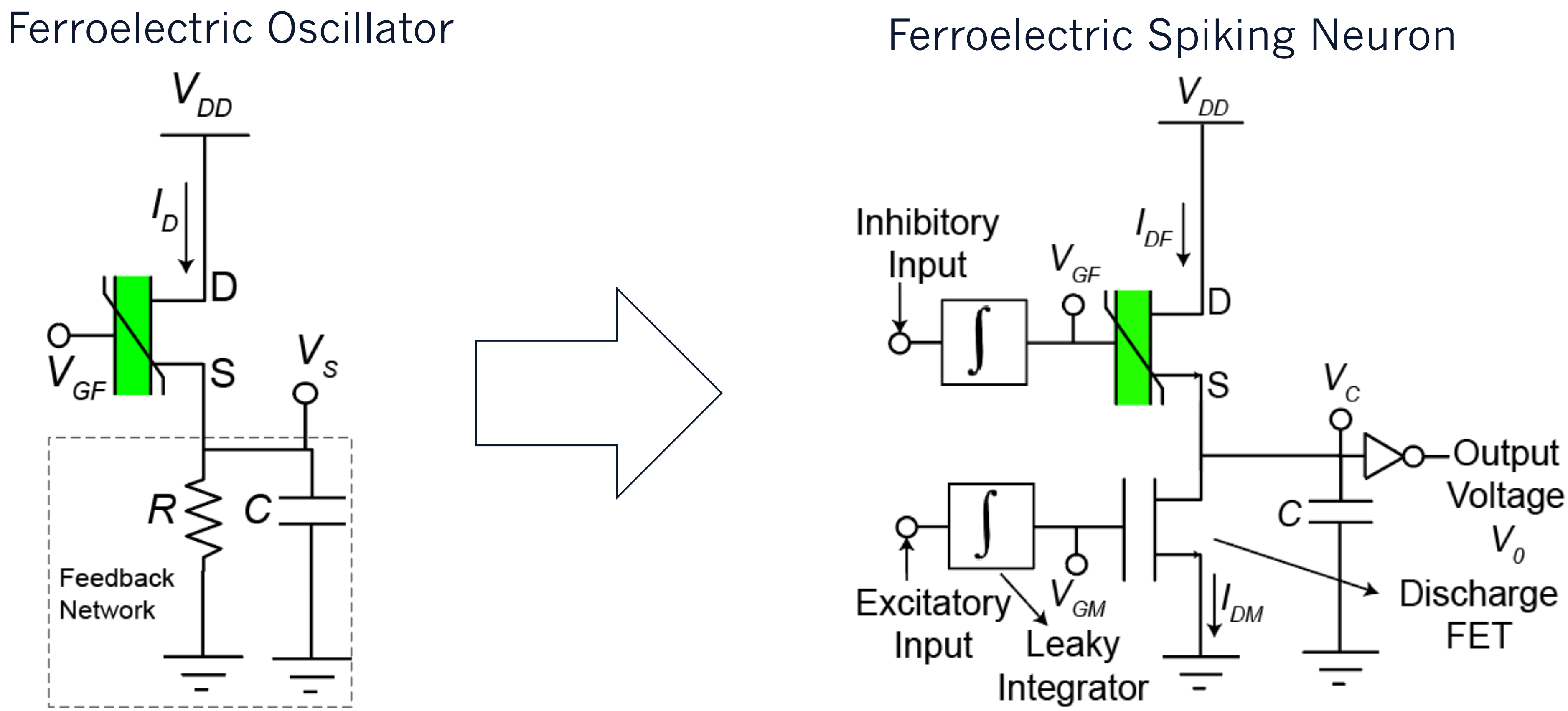




Oscillations stop if proper loadline crossing is not maintained.

Z. Wang et al. *IEEE Electron Device Lett.* vol. 38, no. 11, pp. 1614–1617, 2017.

FROM OSCILLATOR TO SPIKING NEURON



R replaced with a MOSFET; Leaky Integrator Added

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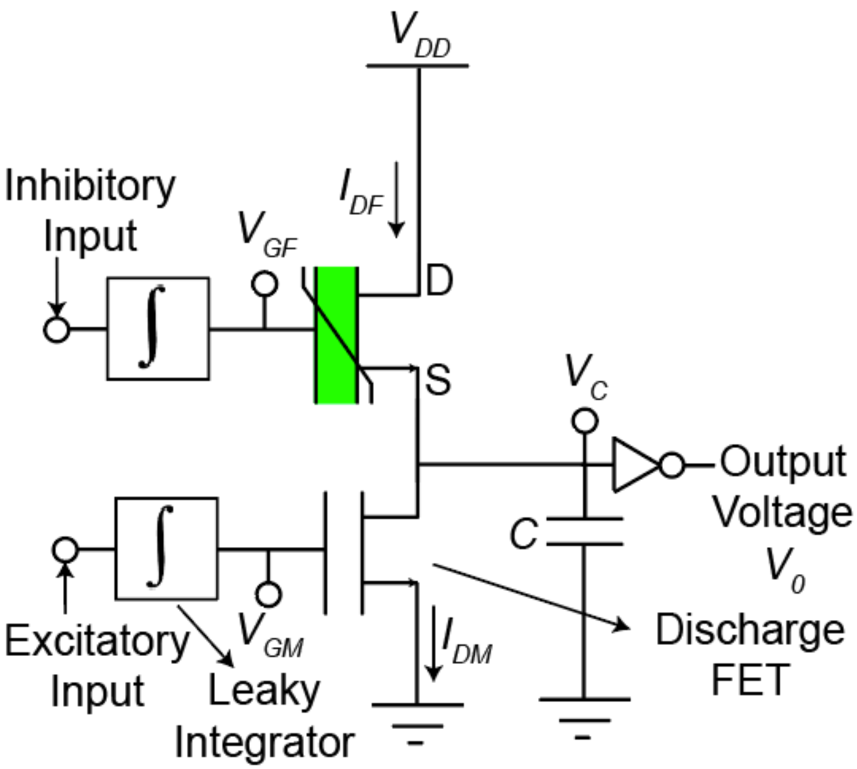
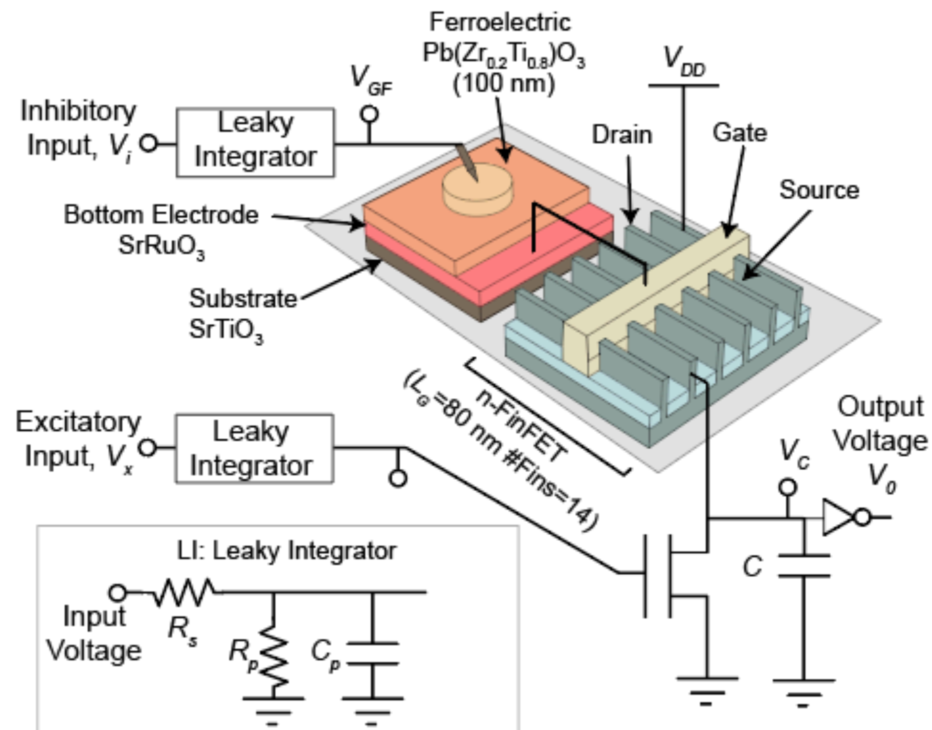
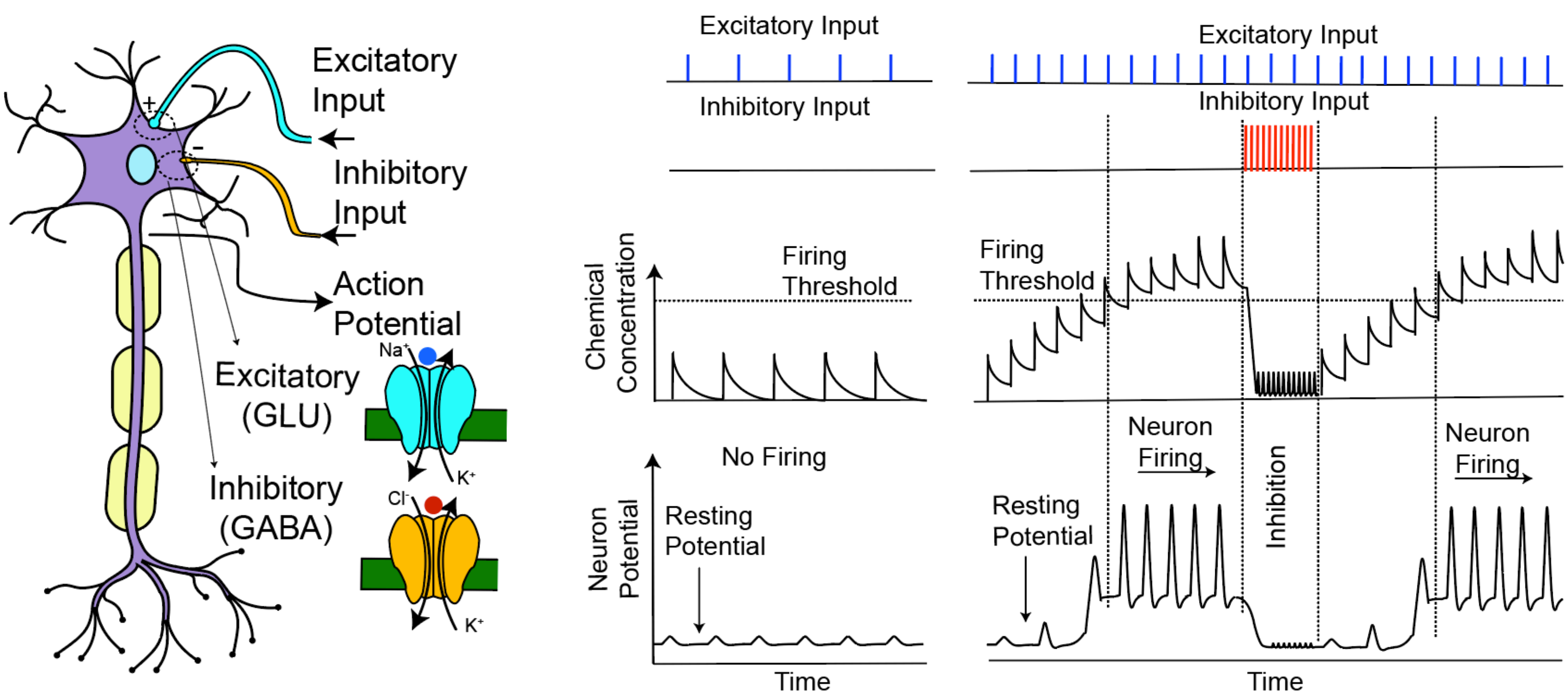
FERROELECTRIC SPIKING NEURON SETUP





(It's amazing that such a setup actually works!)

A Biological Neuron



Biology: Inhibition required for regulation in activation of excitatory neurons; homeostasis.
Bio-inspired computing: High accuracy in unsupervised learning.

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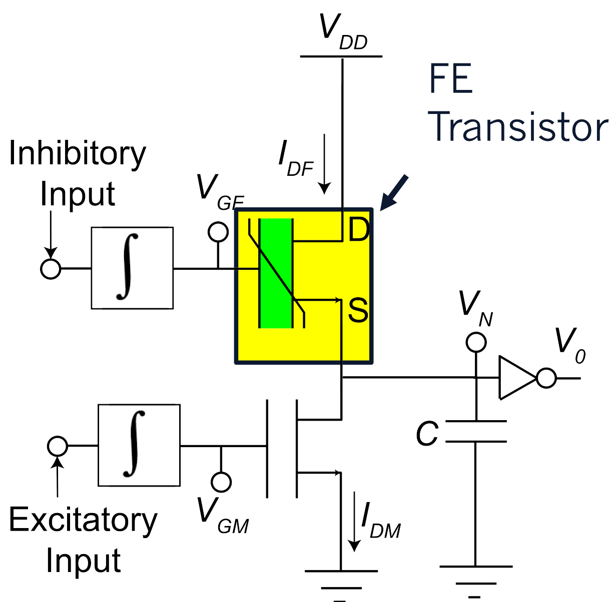
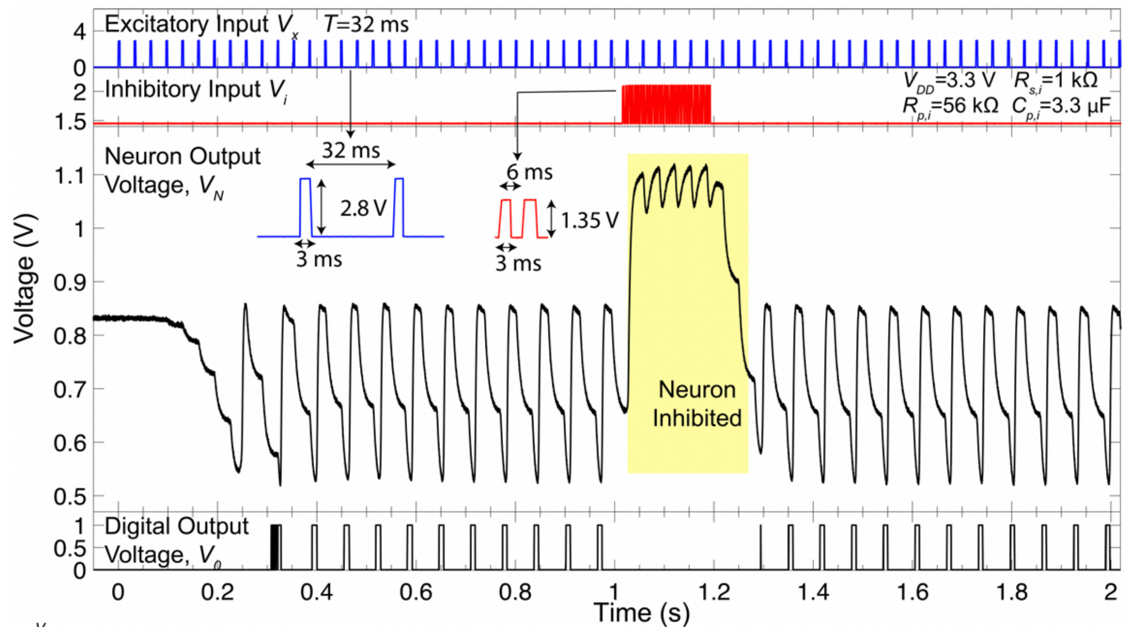
A Ferroelectric Neuron





Z. Wang et al. IEDM 2018

research highlights

NEUROMORPHIC DEVICES

Ferroelectric spiking neurons

2018 IEEE Int. Electron Devices Meet. (in the press)

Brain-like computation using artificial neural networks (ANNs) could provide improved energy efficiency when compared

nature electronics

(2019)

The first demonstration of an artificial neuron with integrated **inhibitory and excitatory** input!

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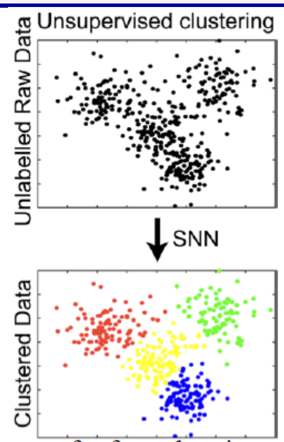
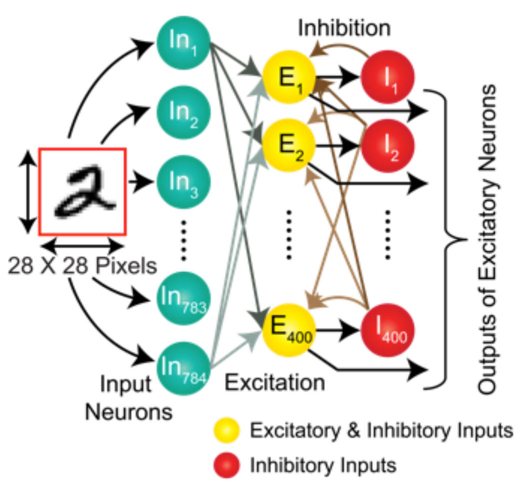
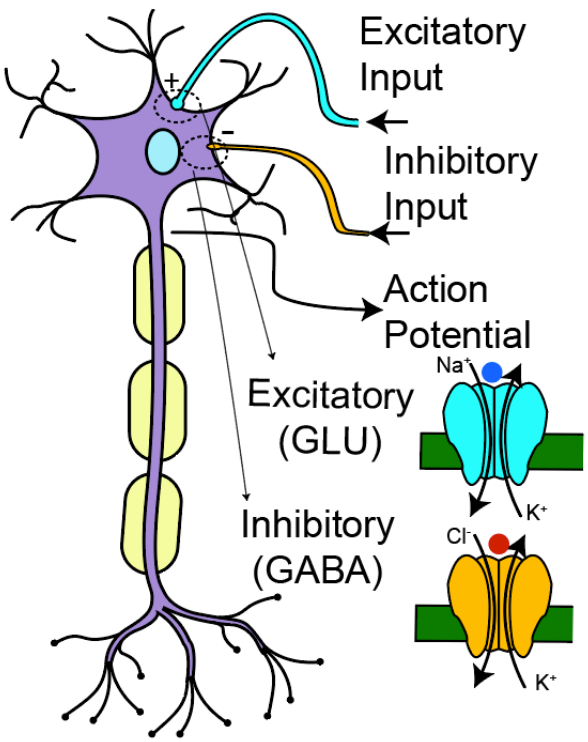
Ferroelectic Spiking Neural Network

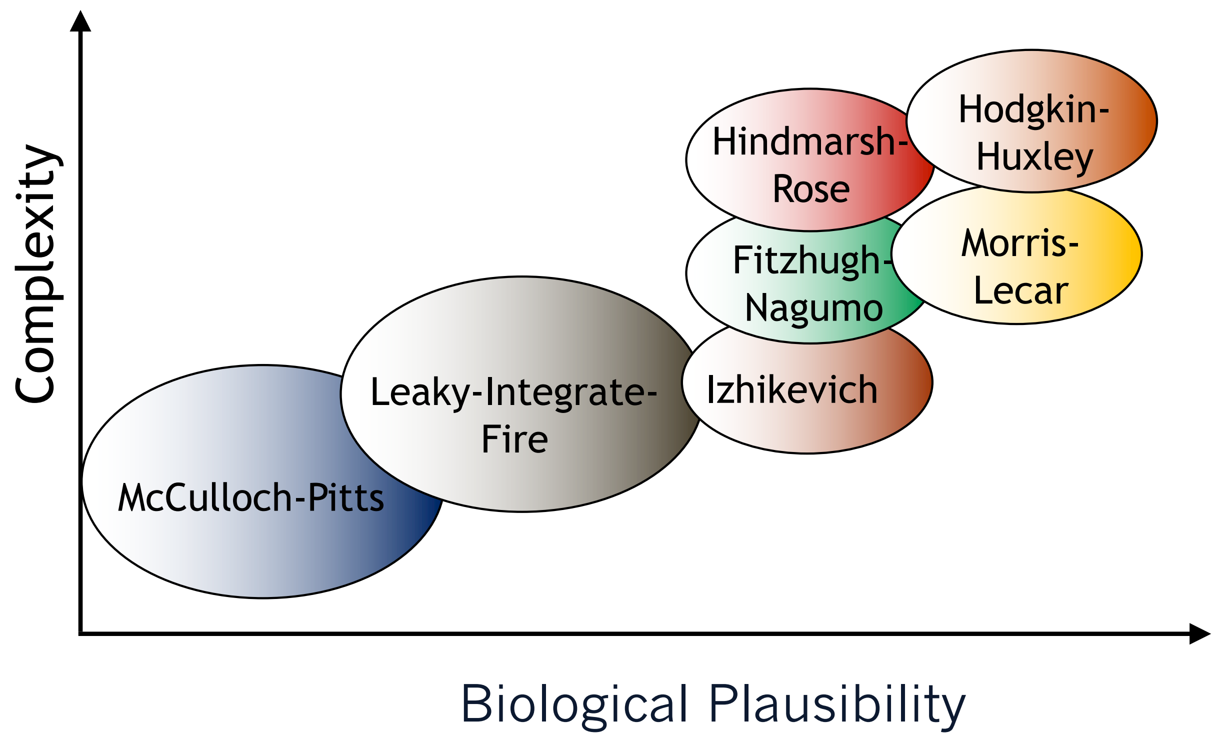




	Indiveri ISCAS 2003	Amravati ISSCC 2018	Jerry et al. VLSI 2017	Current work
Technology	CMOS Analog, Mixed Signal		Emerging Technology	
Neuron Type	LIF	Multiply-Accumulate	LIF	LIF
Network Type	Spiking	Non-spiking	Spiking	Spiking
Data Encoding Architecture	Spike Timing	Multi-level perceptron	Spiking Rate	Spike Timing
Input Type	Excitatory	Excitatory	Excitatory	Excit. & Inhib.
Device Count	15 T	64 T	1T - 1 VO_2	1T - 1 FEFET
Synapse Weight	Pos. & Neg.	Pos. & Neg.	Pos. & Neg.	Pos.
Training & Classification	Unsupervised	Reinforcement	Supervised	Unsupervised
Power	10 nW	125 nW	Not reported	3.6 nW

Landscape of Neuron Models





Schuman, Catherine D., et al. "A survey of neuromorphic computing and neural networks in hardware.", arXiv:1705.06963 (2017).

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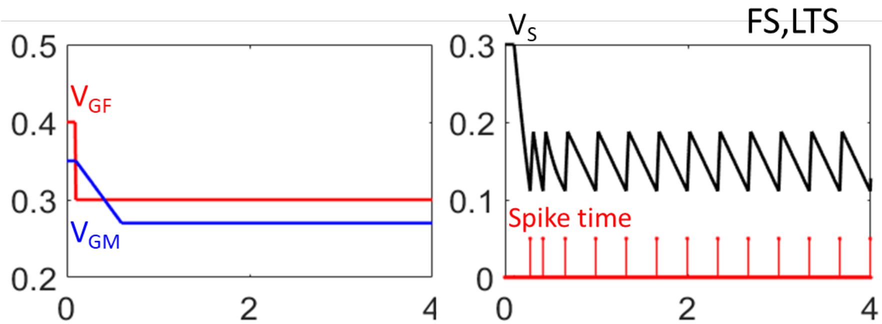
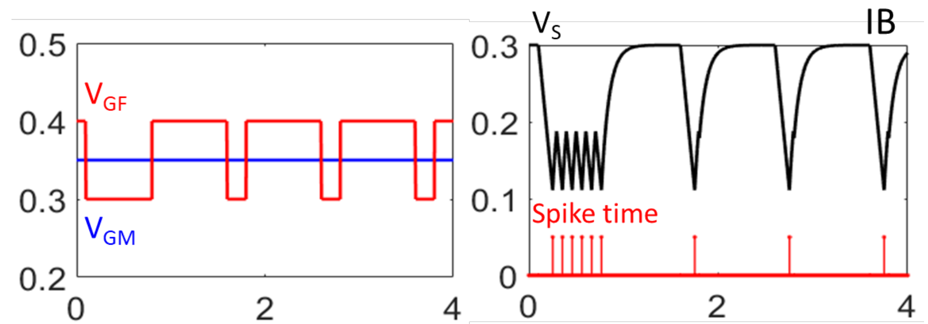
Biomimetic Spiking Patterns in Ferroelectric Neurons

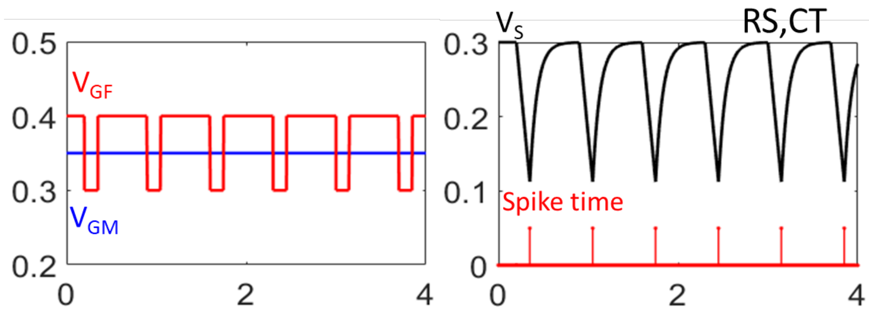
Apply excitatory and inhibitory inputs to mimic different spiking patterns of cortical neurons



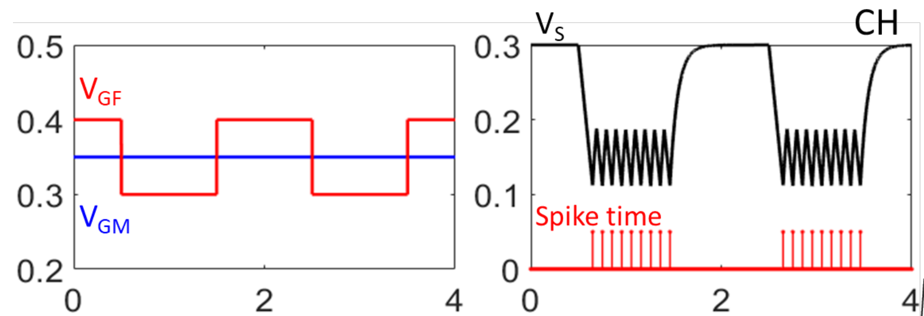
Fast Spiking (FS) and Low Threshold Spiking (LTS)



Regular Spiking (RS) and Thalamo-cortical (TC)



Intrinsically Bursting (IB)



Chattering (CH)

Fan et al. IEEE Electron Dev. Lett. 2019.

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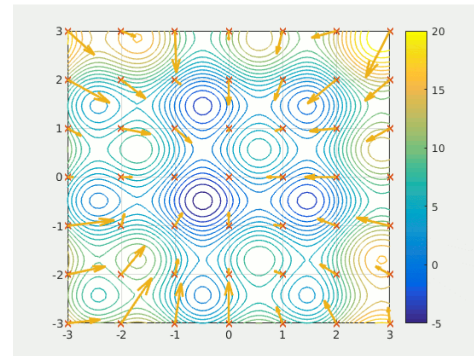
Collective Behavior and Swarm Intelligence

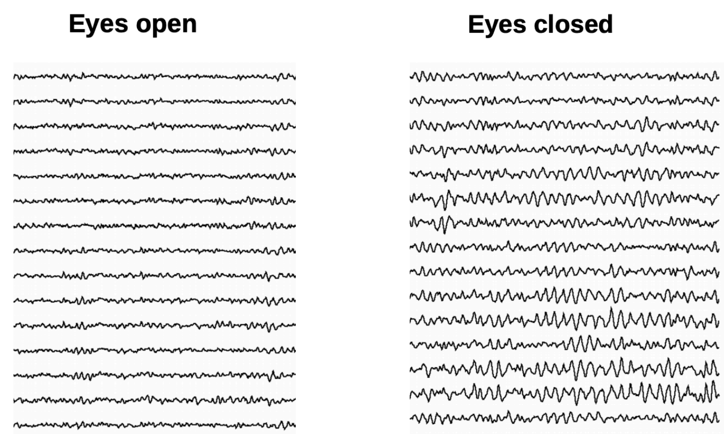
- Neuro-biology and natural swarm behaviors
- Large number of simple agents giving rise to intelligent behavior
- Computationally hard problems (graph coloring, traveling salesman problem etc.)

General Framework

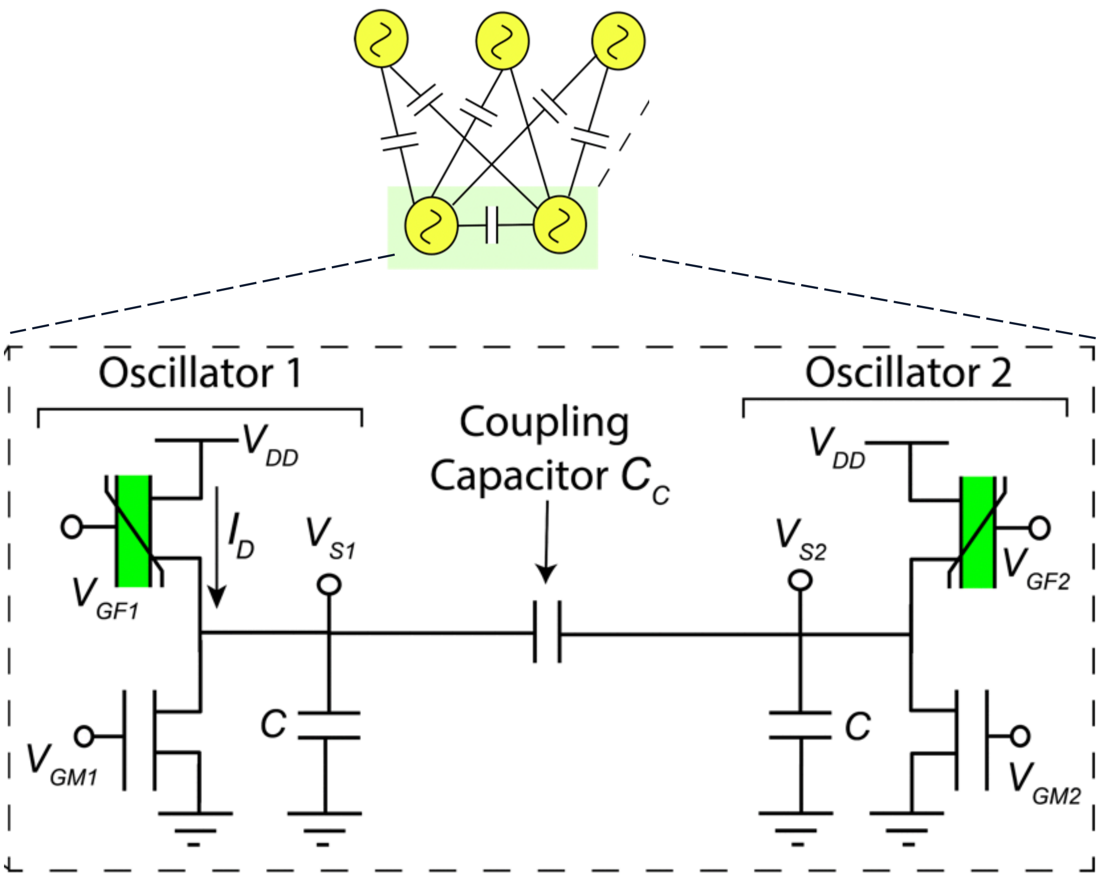


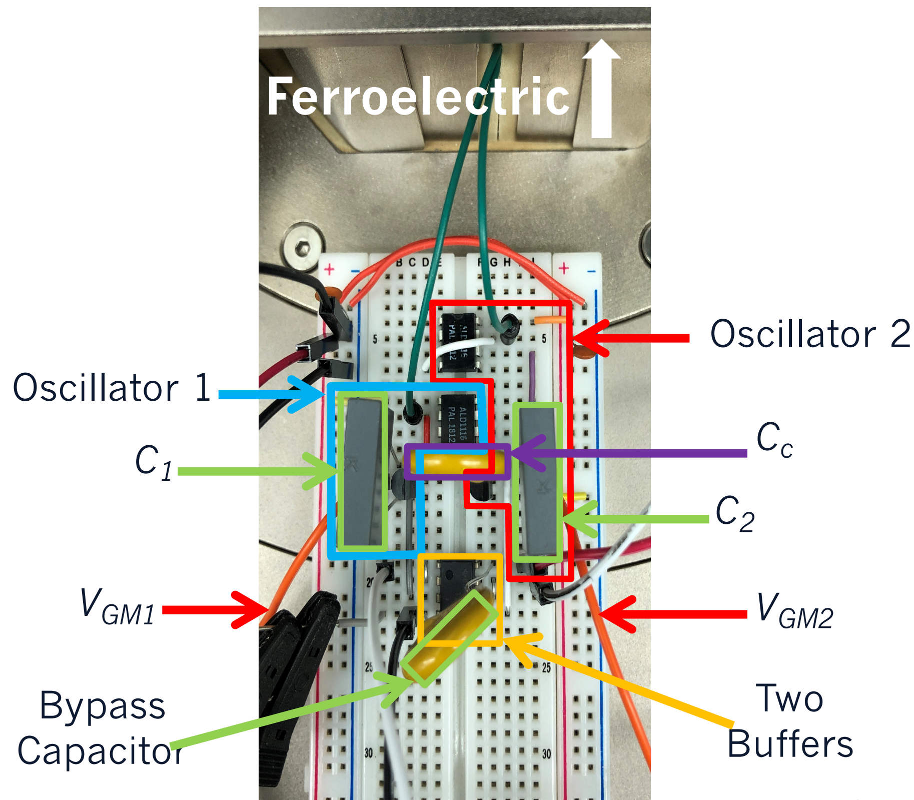
A school of fish and a shark

Collective Spatio-temporal oscillations in Primary Visual Cortex



Coupled Ferroelectric Neurons (Experiments)





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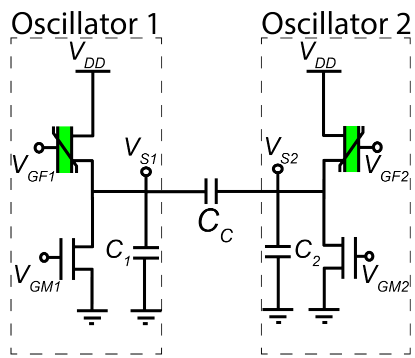
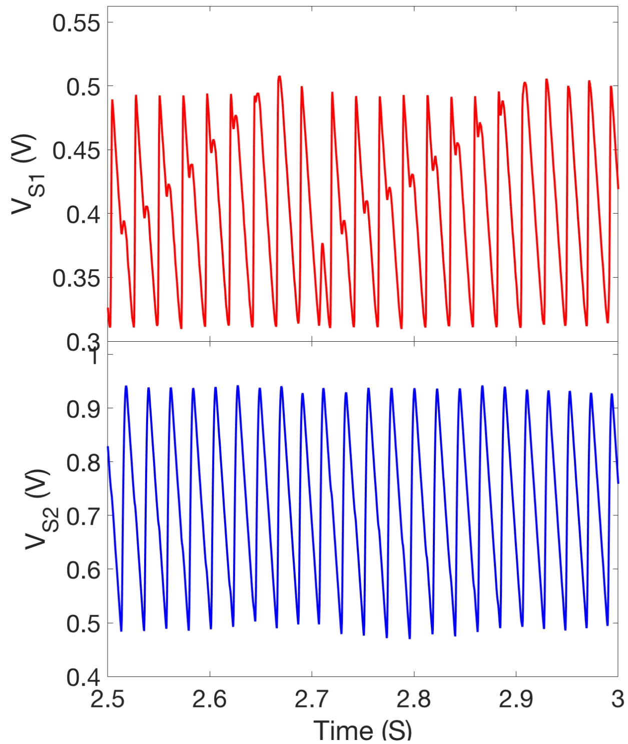
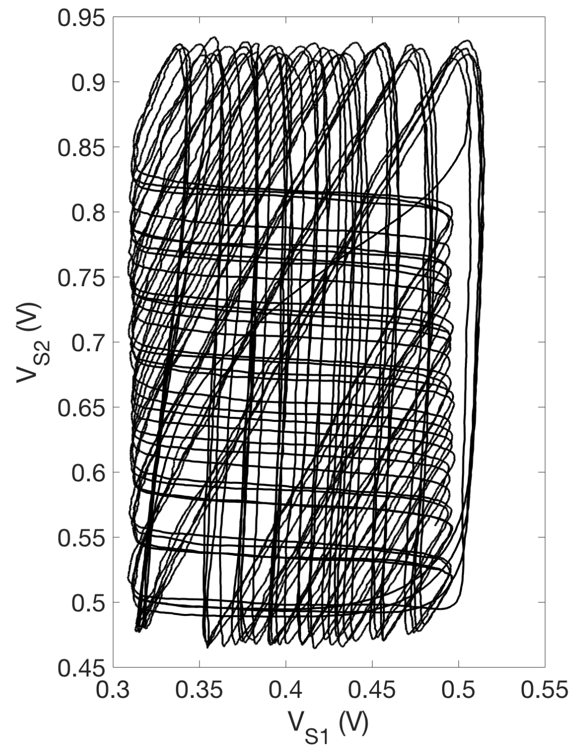
Synchronization Dynamics of Coupled FE Neurons



$V_{GF1}=V_{GF2}=0.6$ V
$V_{GM1}=1.55$ V
$V_{GM2}=1.6$ V
$C_1=C_2=10$ nF
$C_c=1$ nF ←





Two oscillators are weakly coupled, the coupled system is **not synchronized**, showing a non-repetitive crisscross pattern.

Wang et al. (unpublished).

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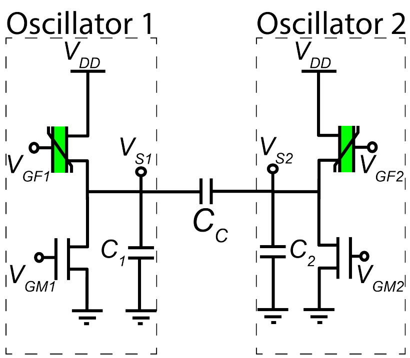
Synchronization Dynamics of Coupled FE Neurons



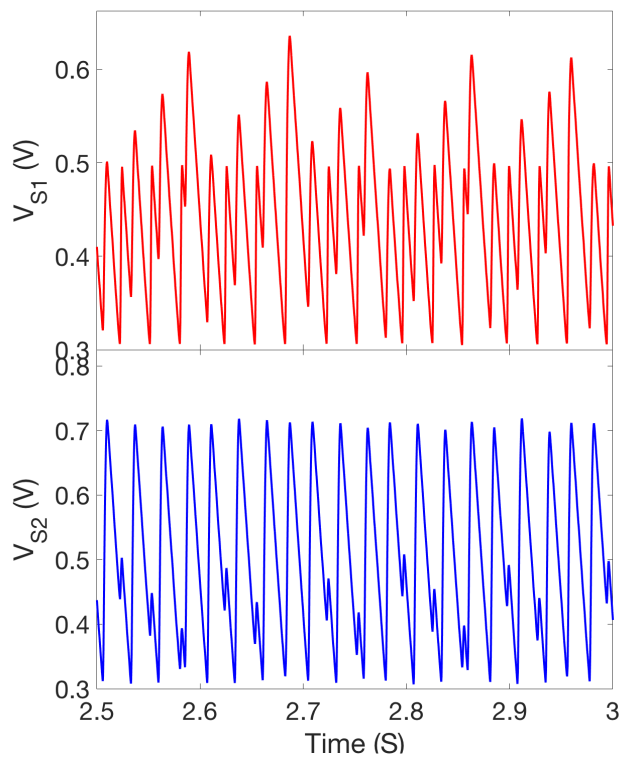
$V_{GF1}=V_{GF2}=0.6$ V

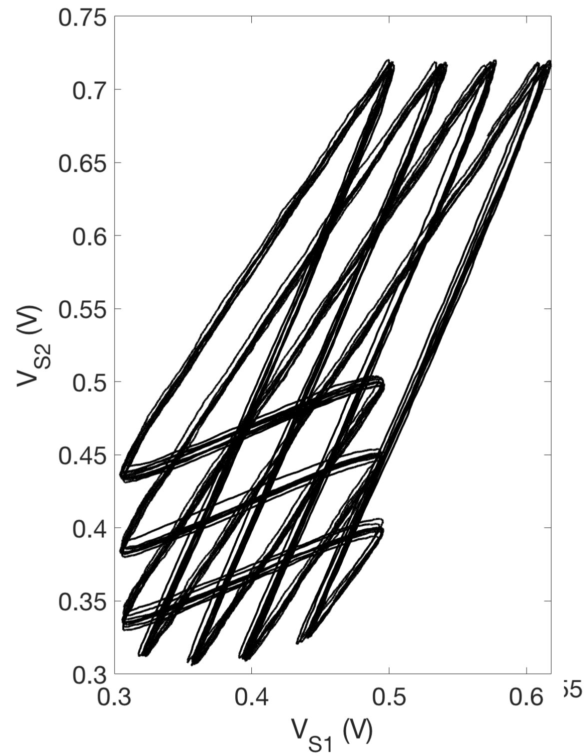
$\mathbf{V_{GM1}=1.55}$ **V**

$\mathbf{V_{GM2}=1.6}$ **V**

$C_1=C_2=10$ nF

$\mathbf{C_c=10}$ **nF**





The coupled strength of two oscillators is increased, the coupled system is **synchronized**, showing a periodic pattern.

Wang et al. (unpublished).

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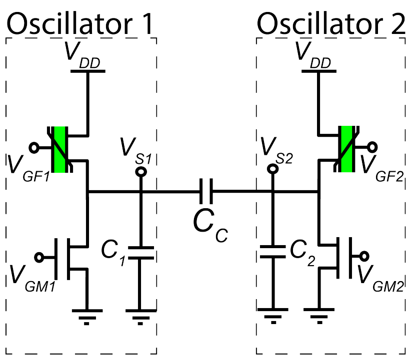
Synchronization Dynamics of Coupled FE Neurons



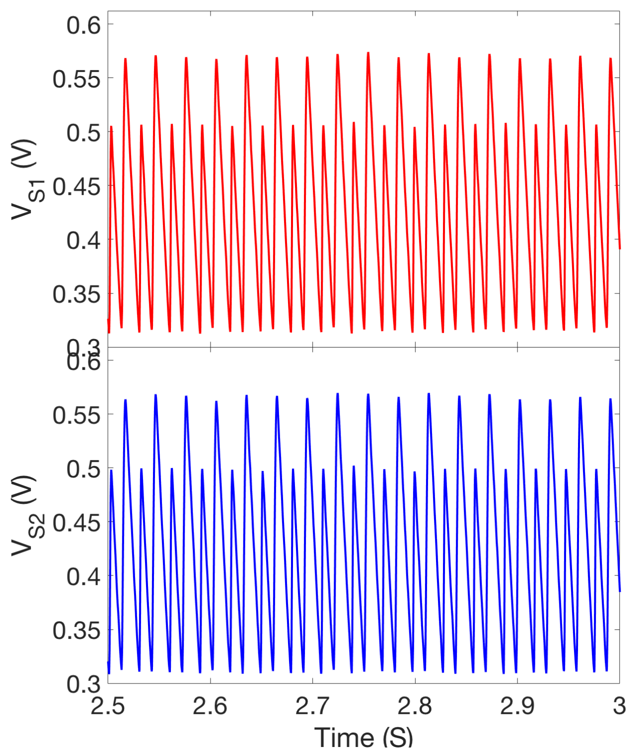
V_{GF1}=V_{GF2}=0.6 V

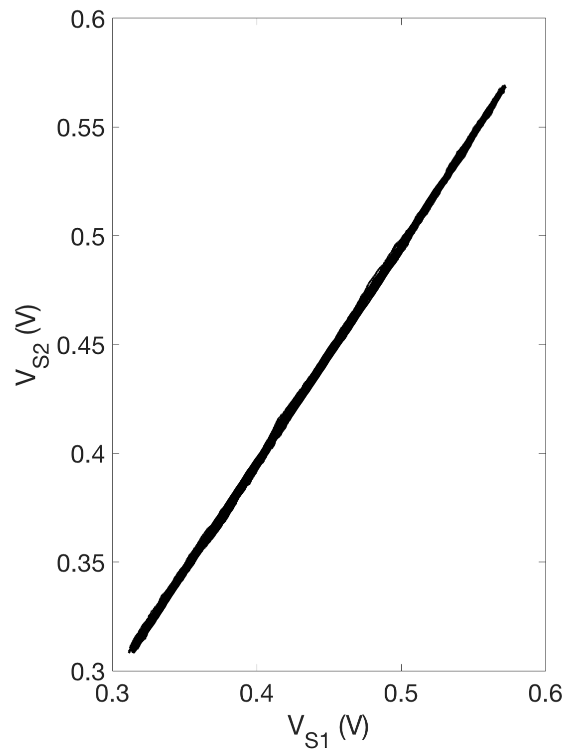
V_{GM1}=1.55 V

V_{GM2}=1.6 V

C_1=C_2=10 nF

C_c=1 uF ⟵





Two oscillators are strongly coupled, the coupled system is **synchronized**. In fact, two oscillators have identical waveforms.

Wang et al. (unpublished).

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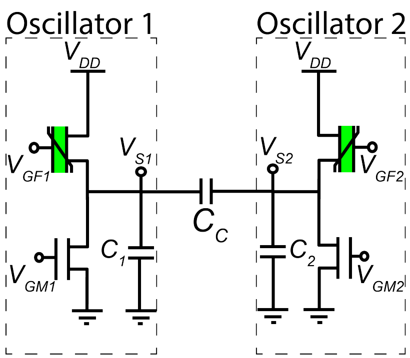
Synchronization Dynamics of Coupled FE Neurons



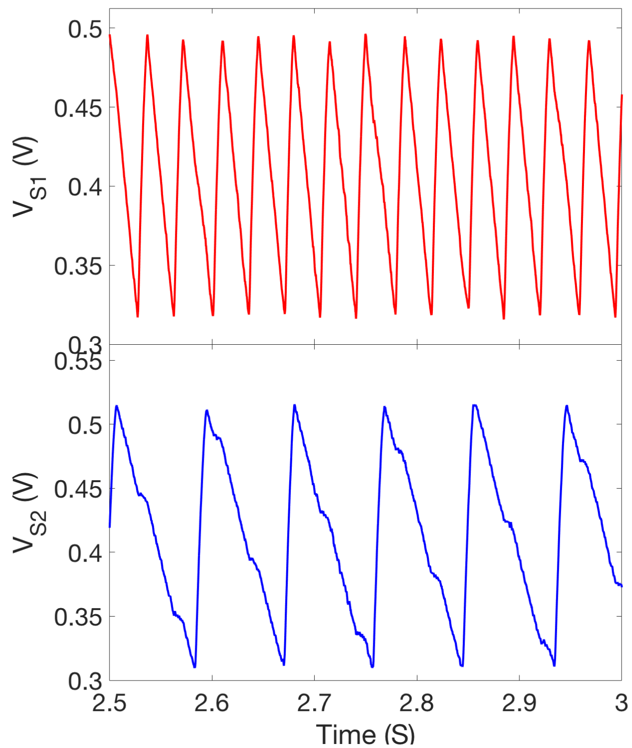
V_{GF1}=V_{GF2}=0.6 V

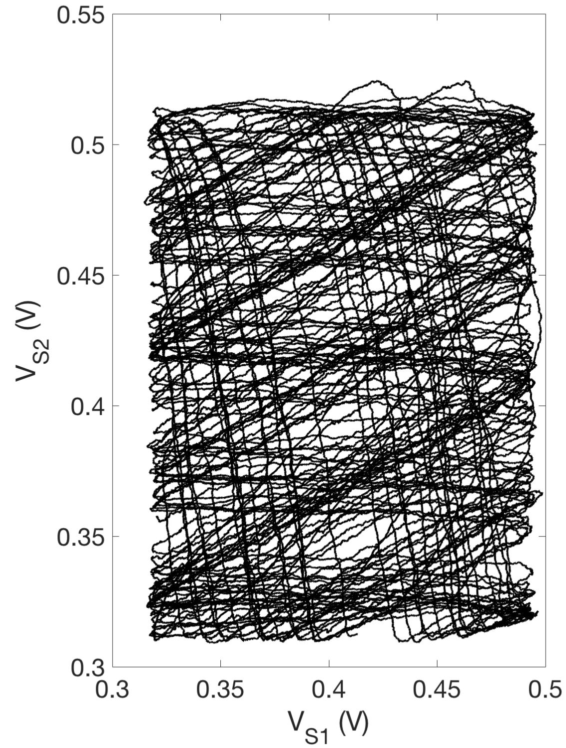
V_{GM1}=1.7 V

V_{GM2}=1.6 V

C_1=C_2=100 nF

C_c=10 nF





Increase the difference between V_{GM} *leading to larger frequency difference of two individual oscillators, as the result the system is* ***not synchronized*** *at* C_c*=10 nF.*

Wang et al. (unpublished).

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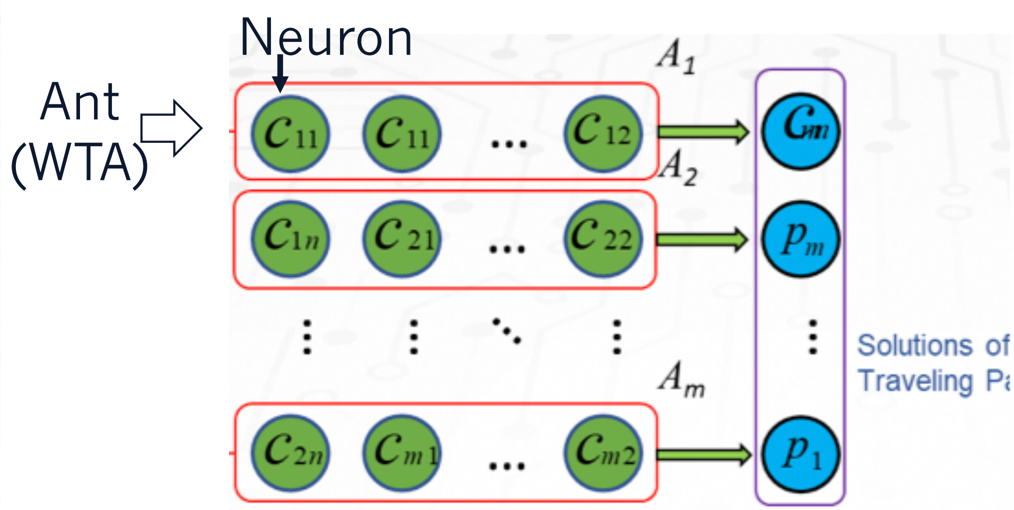
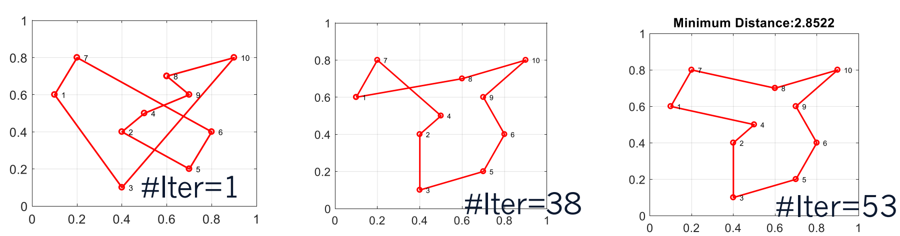
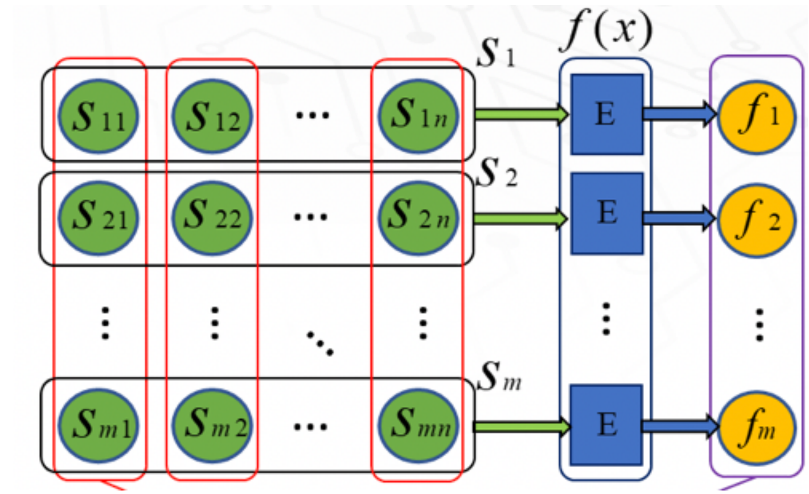
Ant Colony Algorithm for Traveling Salesman Problem

Optimization of Continuous Objective Function





FE Neuron: Regular Spiking (RS) mode.
Inhibition Needed.
Phase based Representation.



FE Neuron: Fast Spiking (FS) mode.
Inhibition disabled.
Rate-based Representation

Fan et al.
Frontiers in Neuroscience 2019.

Georgia Tech

Semiconductor Industry and Ferroelectrics

"AI could allow semiconductor companies to capture <u>40 to 50 percent</u> of total value from the technology stack, representing the best opportunity they've had in decades."

Historically the fraction has been 10-20% for the semiconductor industry!

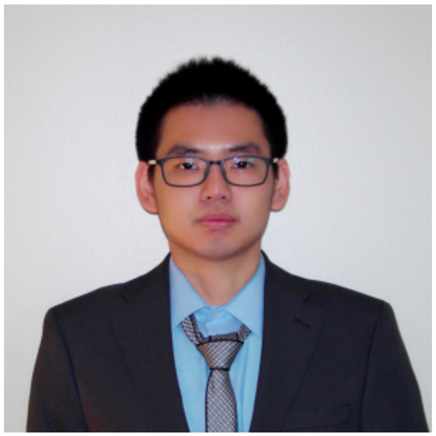
https://www.mckinsey.com/industries/semiconductors/our-insights/artificial-intelligence-hardware-new-opportunities-for-semiconductor-companies.

Georgia Tech

Thank you and Acknowledgements

Experiments Design And Implementation

Zheng Wang



Device and Circuit Modeling

Jorge Gomez
Suman Datta
(Notre Dame)

Spiking Neural Network Implementation

Brian Crafton
Arijit Raychowdhury
(Georgia Tech)

Also

Ruijiun Xu
Aileen Luo
Lane Martin
(Berkeley)

Zoran Krivokapic

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