28.7: Pairwise Coupled Hybrid Vanadium Dioxide-MOSFET (HVFET) Oscillators for Non-Boolean Associative Computing

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PENNSTATE 1855

Wednesday: 11:35 AM
Session: CDI

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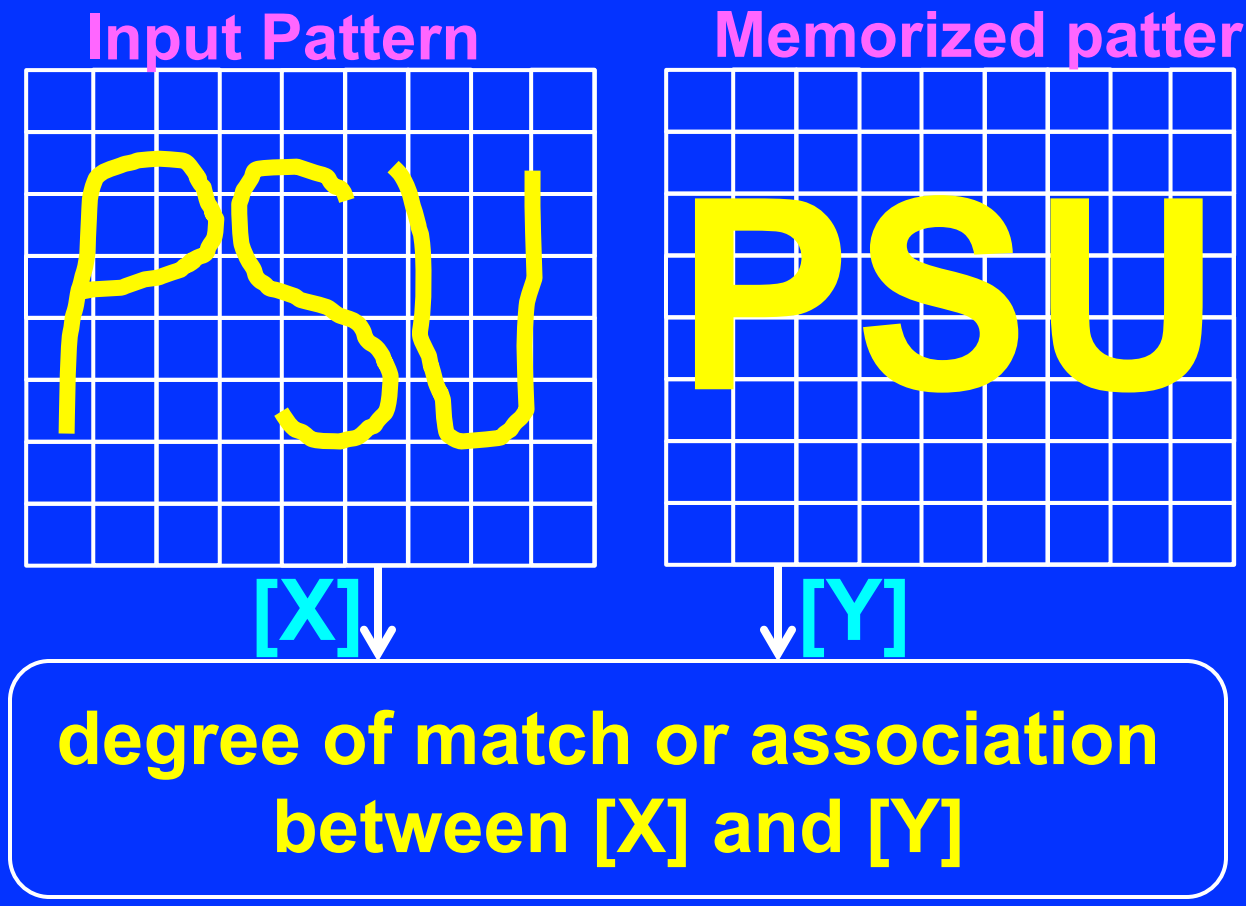
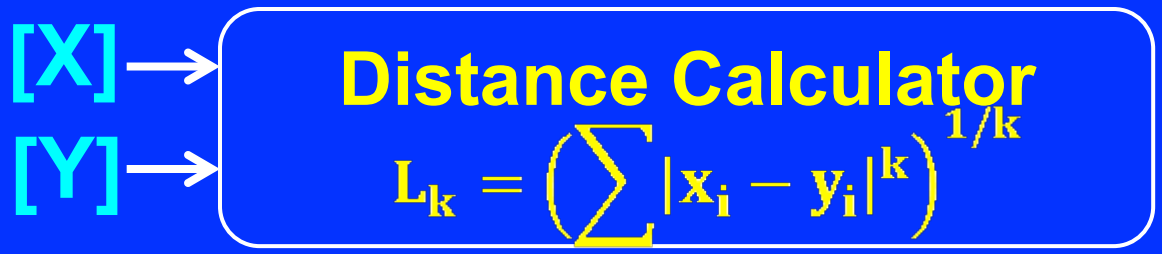
DEPARTMENT OF THE NAVY ONR Science & Technology

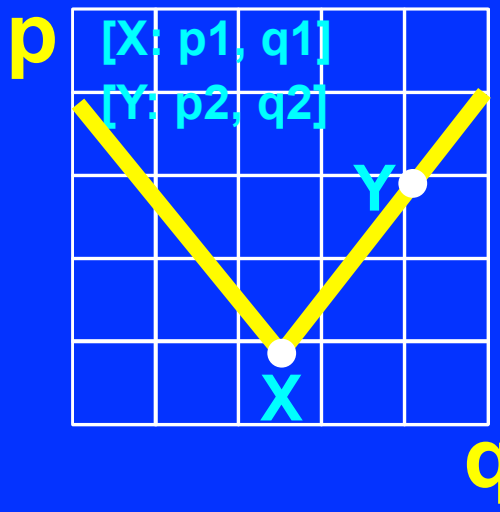
Associative Computing



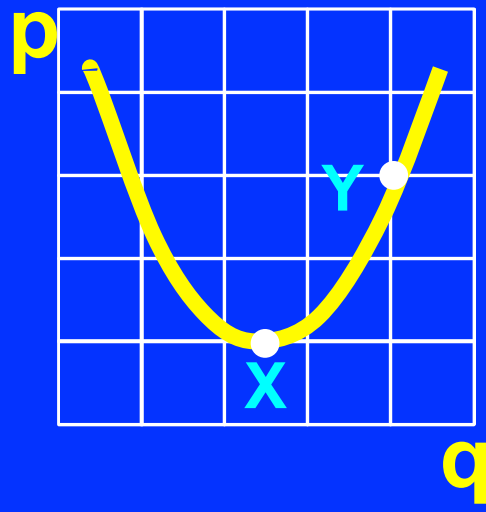
- Applications: Data recognition, mining and classification
  - -Pattern / Image recognition
  - -Visual Saliency

Distance norm for Associative processing

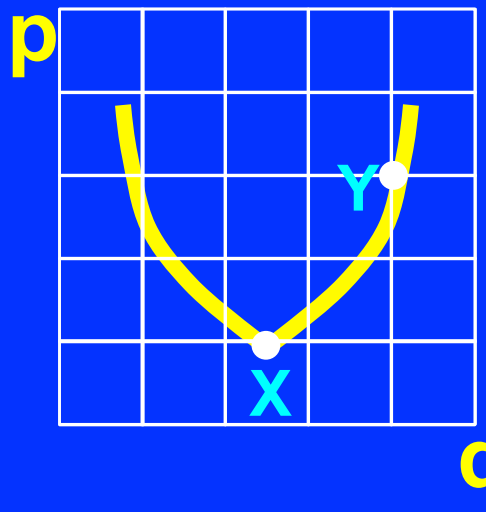




Absolute value difference (L_1)



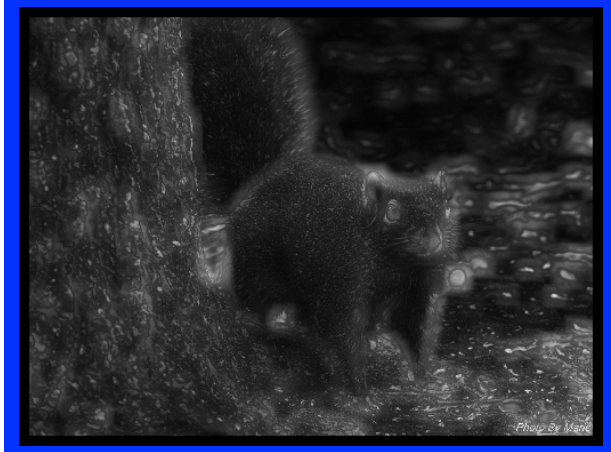
Square of distance (L_2)



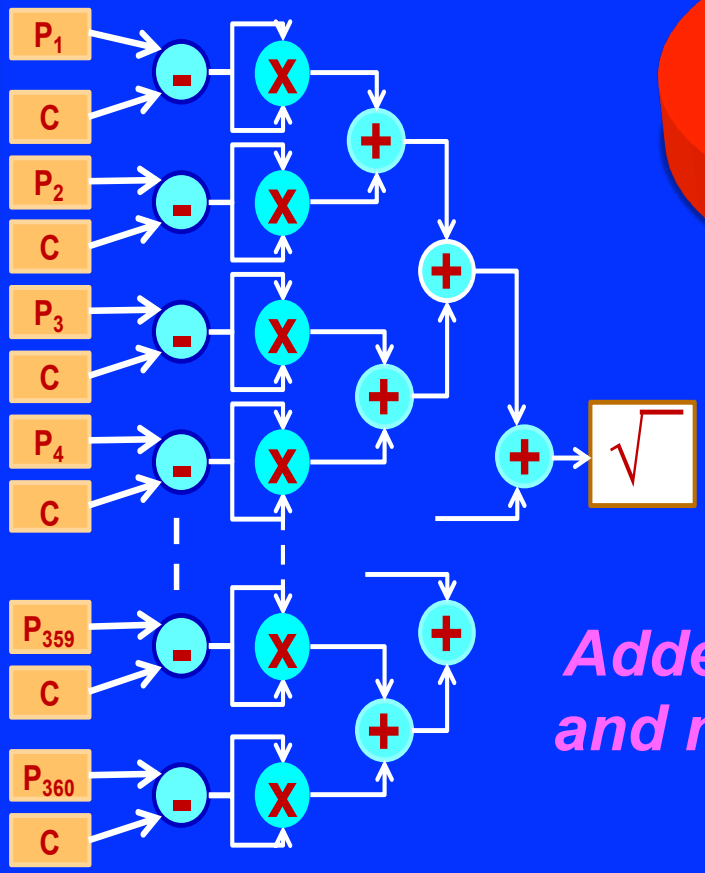
Fractional distance (L_k; k<1)

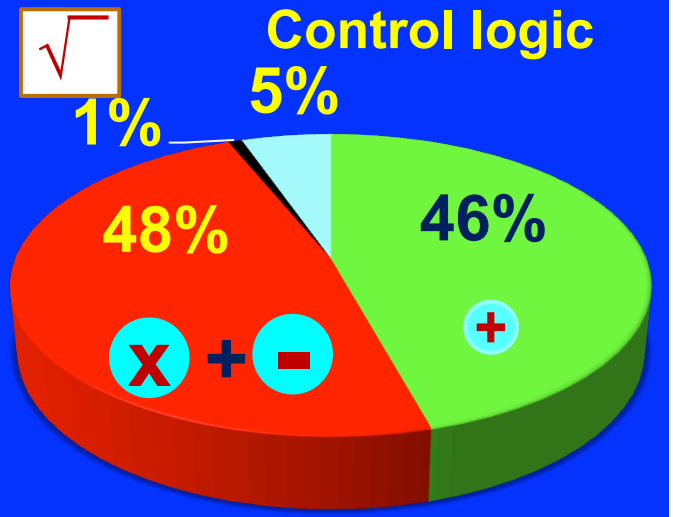
- An associative computing platform must compute distance

Euclidean Distance Calculation using CMOS Accelerator



32nm CMOS accelerator



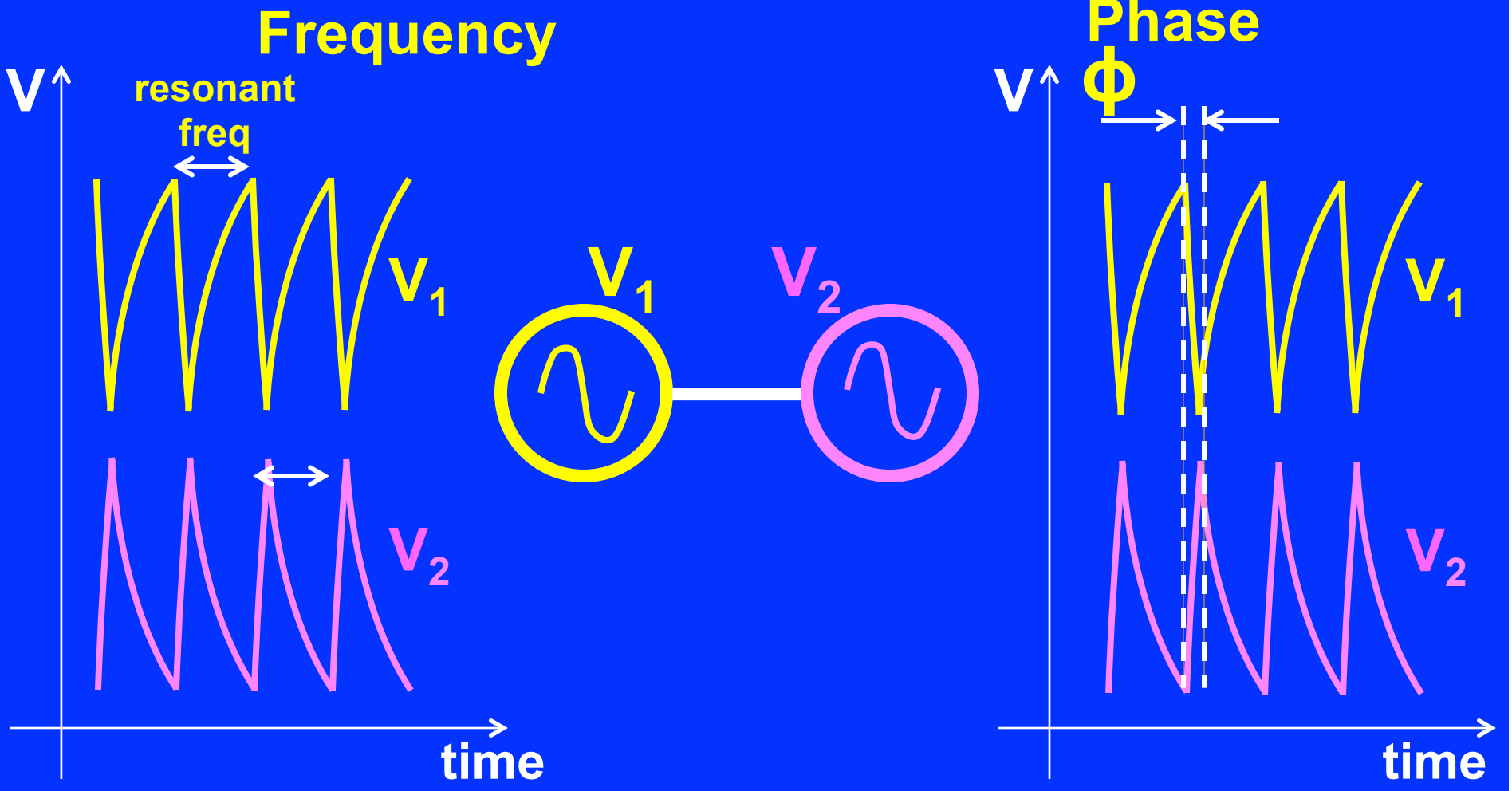


13.1mW
&
~500,000 gates

Adder tree, subtractors and multipliers: A power bottleneck

- Boolean bottleneck in Adder tree and Square root (500,000 gates!)
- Evaluate an alternate non-Boolean architecture to overcome bottleneck

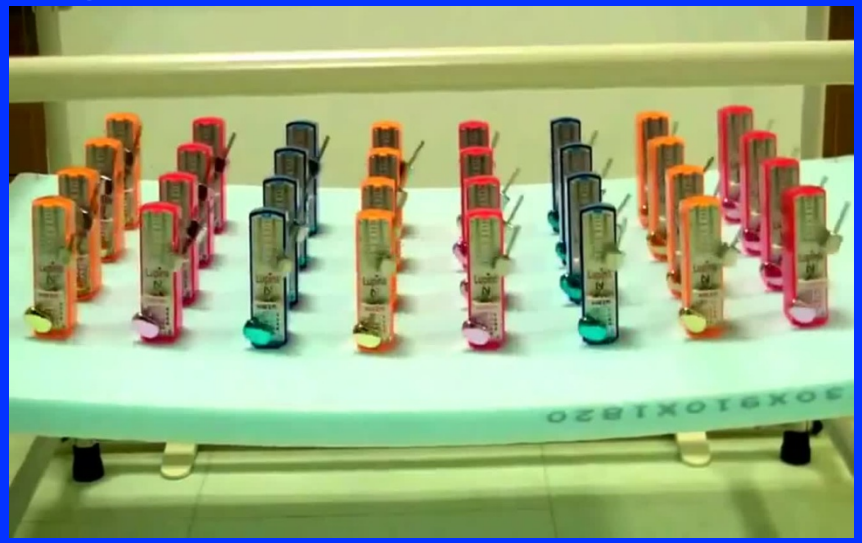
Non-Boolean Computing with Synchronized Oscillators



➢Use synchronization dynamics (phase, frequency) of coupled oscillators as computational state variable

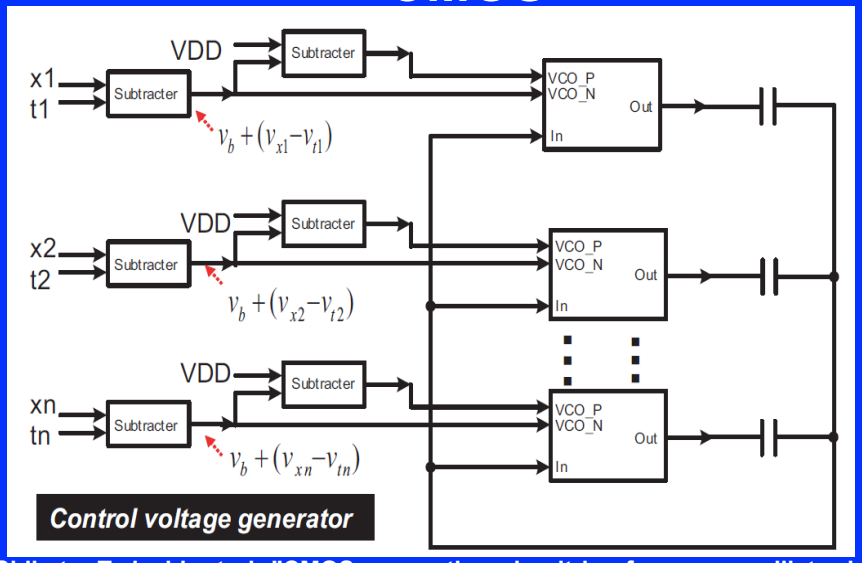
Coupled Oscillatory Systems

Synchronization of Metronomes



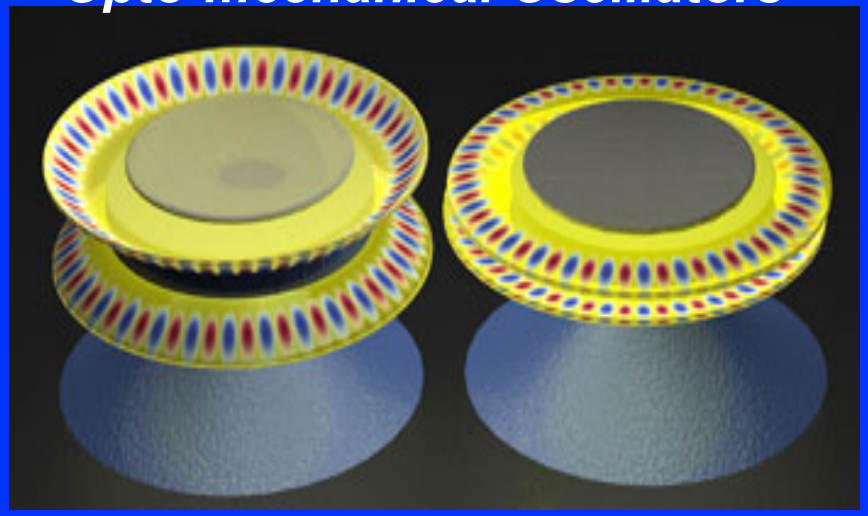
https://www.youtube.com/watch?v=JWToUATLGzs; (Ikelguchi Lab)

CMOS



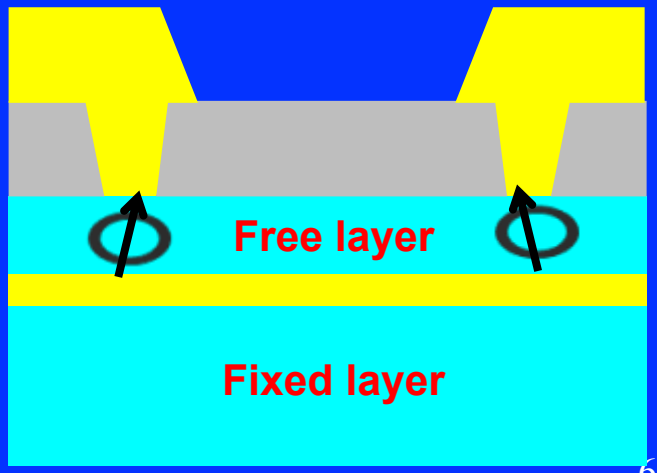
Shibata, Tadashi, et al. "CMOS supporting circuitries for nano-oscillator-based associative memories." *CNNA, 2012 13th International Workshop on*. IEEE, 2012.

Opto-mechanical Oscillators



Zhang, Mian, et al. "Synchronization of micromechanical oscillators using light." *Physical review letters* 109.23 (2012): 233906.

Spin Torque Oscillators



Kaka, Shehzaad, Matthew R. Pufall, William H. Rippard, Thomas J. Silva, Stephen E. Russek, and Jordan A. Katine. "Mutual phase-locking of microwave spin torque nano-oscillators." *Nature* 437, no. 7057 (2005): 389-392.

Outline

- Vanadium dioxide (VO_2) based relaxation oscillators
  - Phase transition in VO_2
  - Oscillator demonstration via resistive feedback
  - Hybrid VO_2-MOSFET (HVFET) oscillator
- Pairwise Coupled HVFET Oscillators
- Computing with HVFET Oscillators
  - Phase as computation state variable
- Power Consumption and benchmarking
- Summary

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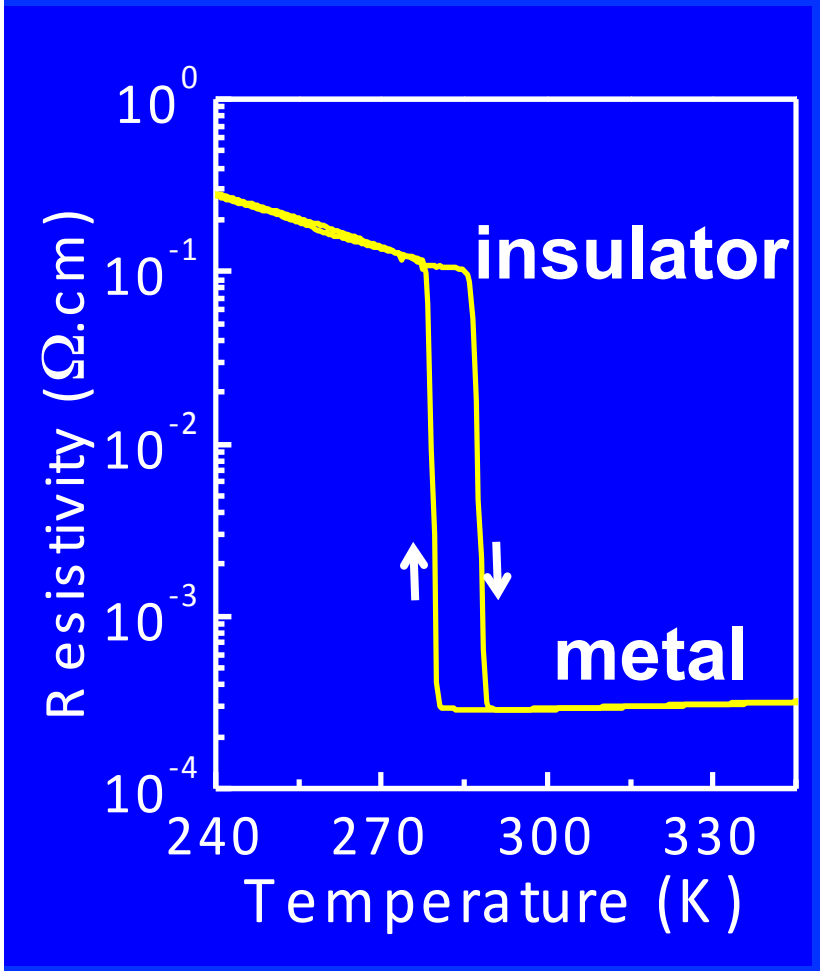
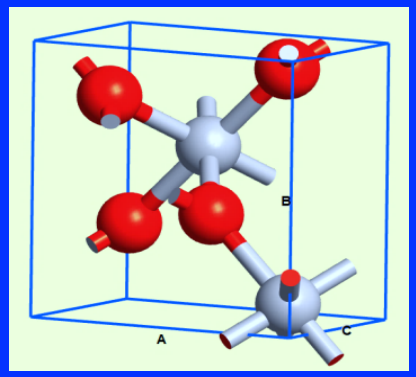
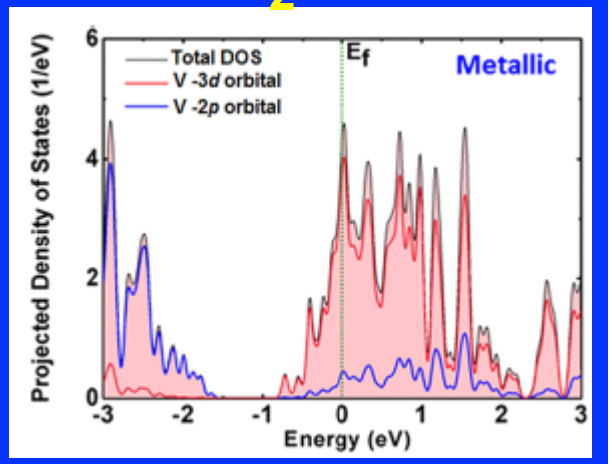
Insulator-metal phase transition in VO_2



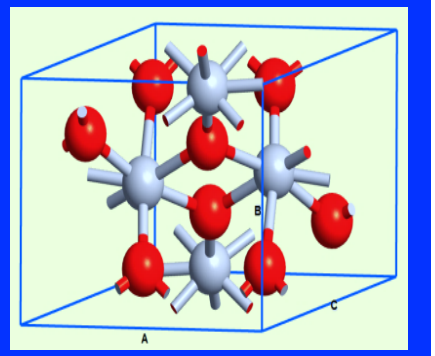
Metallic VO_2



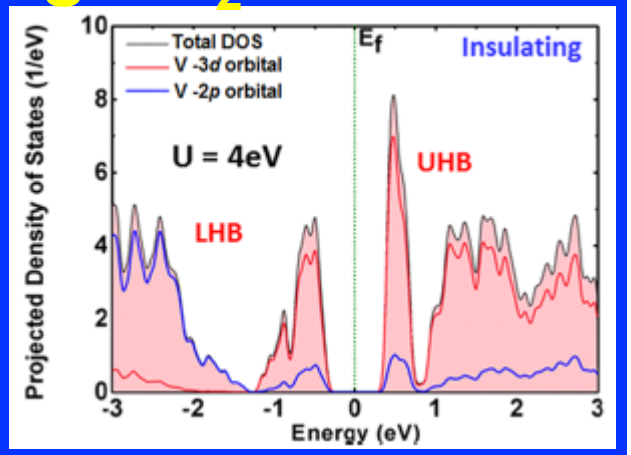
rutile



Insulating VO_2



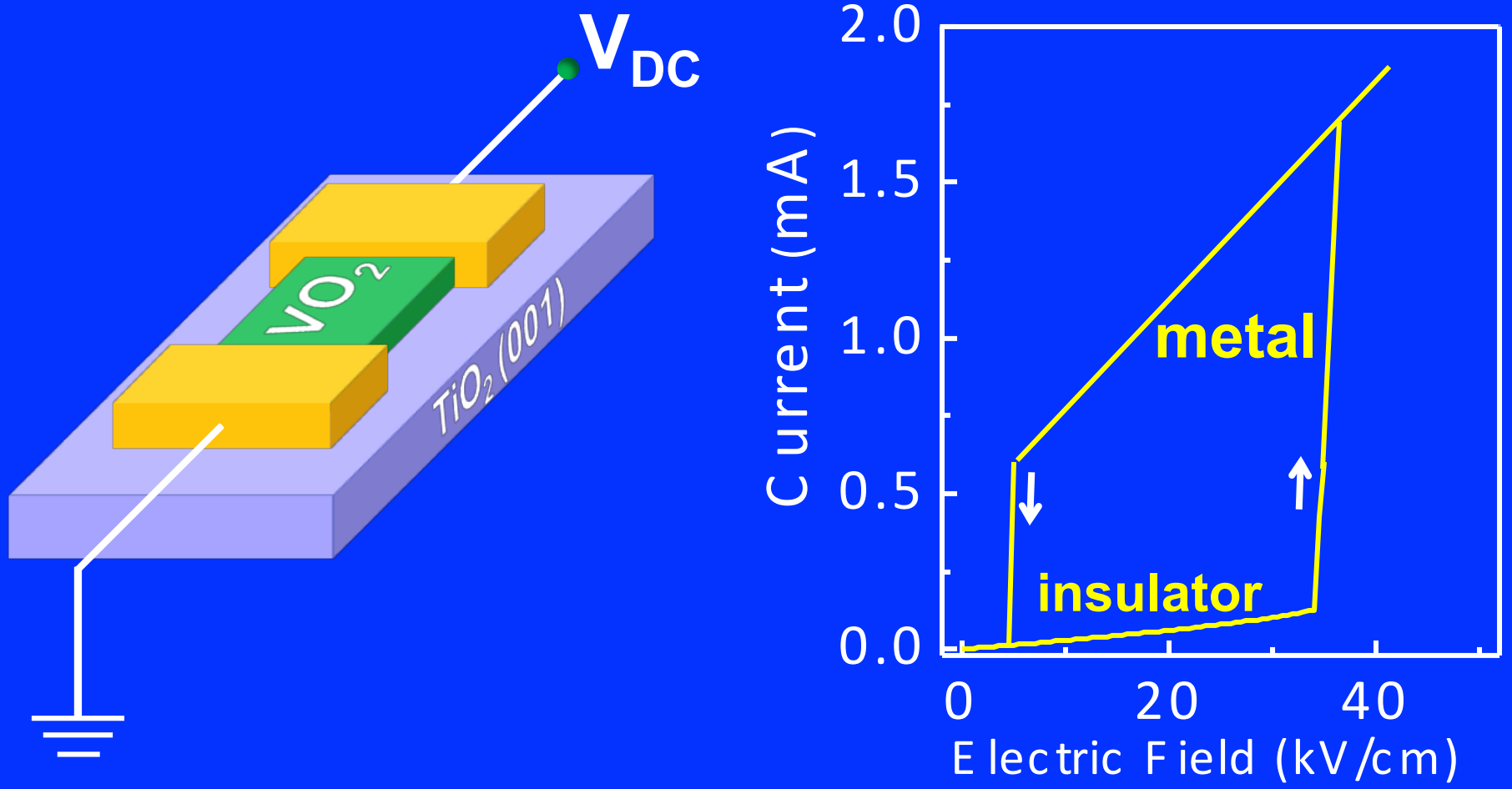
monoclinic



➢ **Abrupt change in VO_2 resistivity through electron correlation dynamics in ultra-thin VO_2 films.**

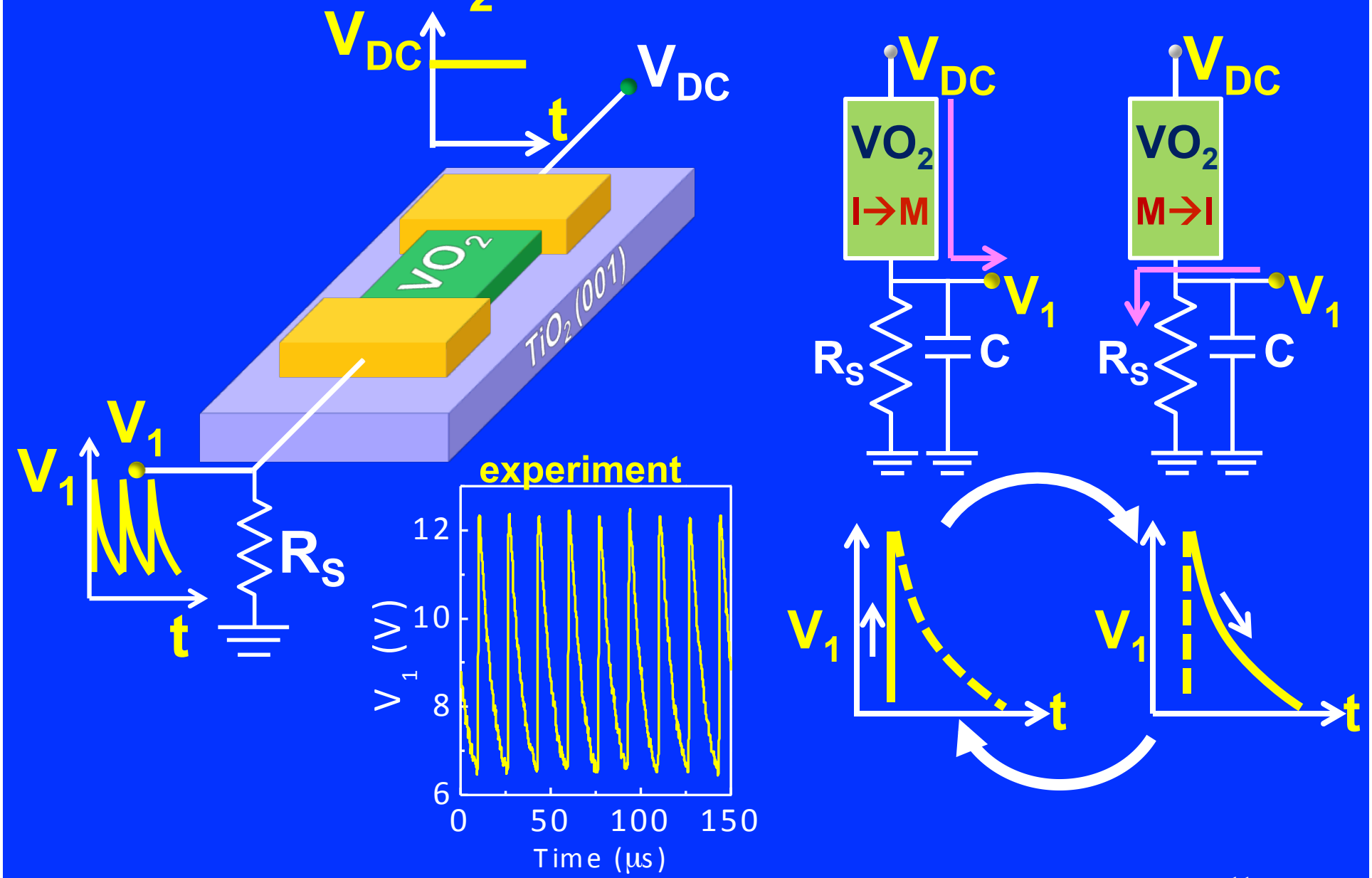
M. Huefner, R. Ghosh, E. Freeman, N. Shulka, H. Paik, D. G. Schlom, and S. Datta "Hubbard Gap Modulation in Vanadium Dioxide Nanoscale Tunnel Junctions", *Nano Letters*, October 2014.

Electrically induced phase transition



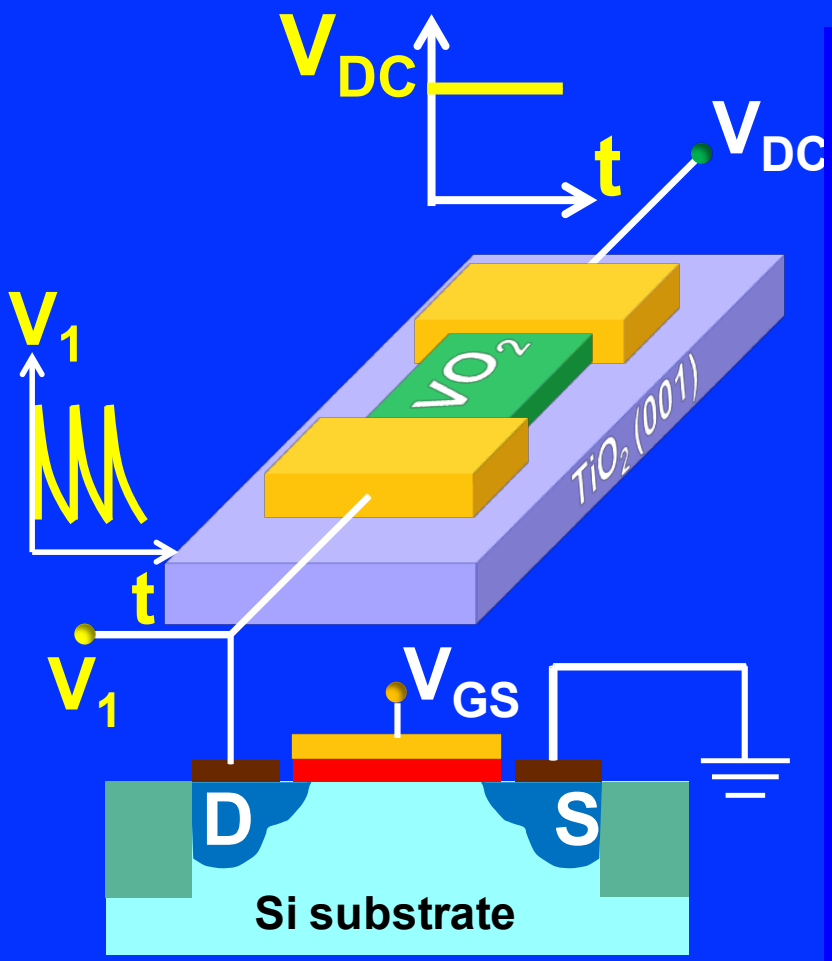
➢**Abrupt, hysteretic phase transition can be electrically triggered**

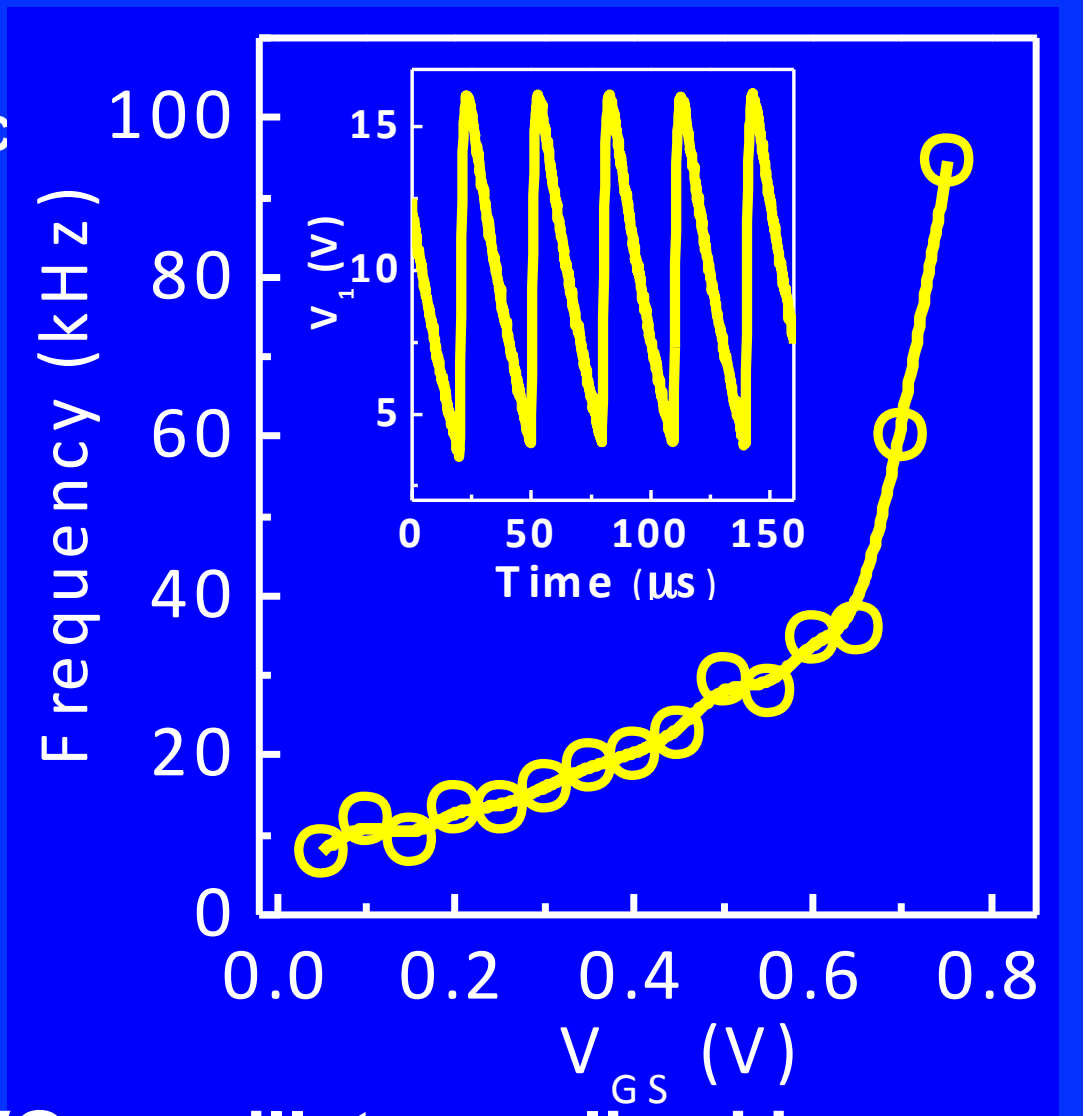
VO_2 based Oscillators



➢ Series resistance (R_S) can enable oscillations

Hybrid VO_2-MOSFET (HVFET) oscillator





➢ Voltage controlled VO_2 oscillator realized by replacing R_S with a MOSFET (HVFET Oscillator)

Outline

- Vanadium dioxide (VO_2) based relaxation oscillators
  - Phase transition in VO_2
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- **Pairwise Coupled HVFET Oscillators**
- Computing with HVFET Oscillators
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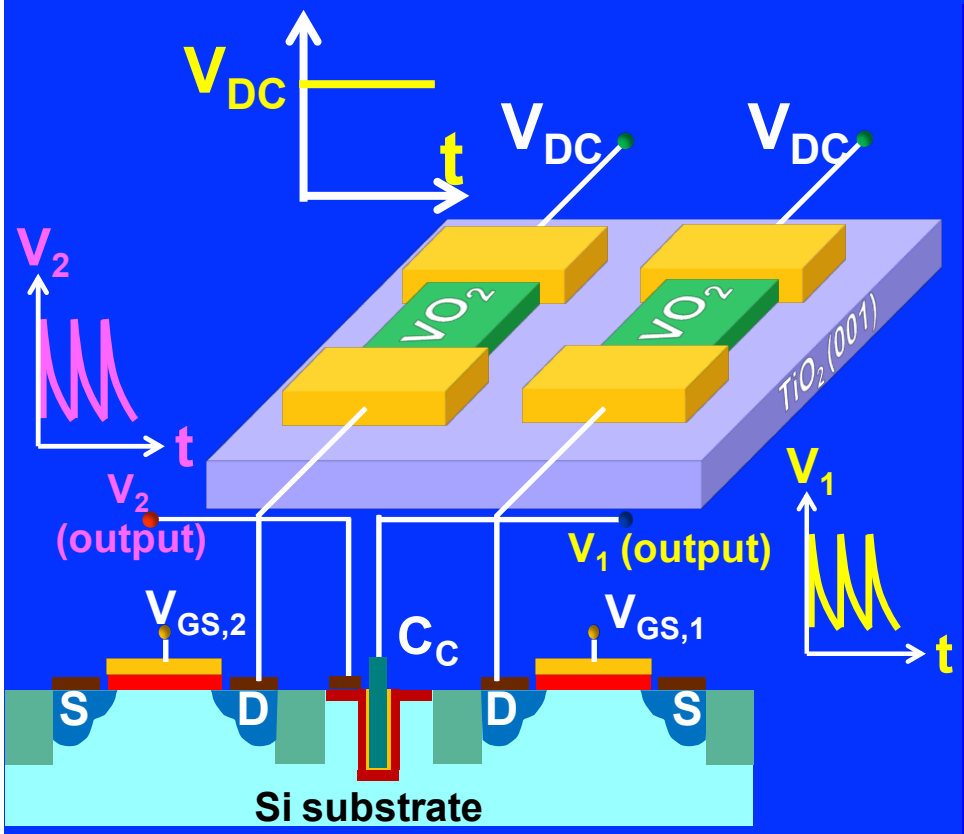
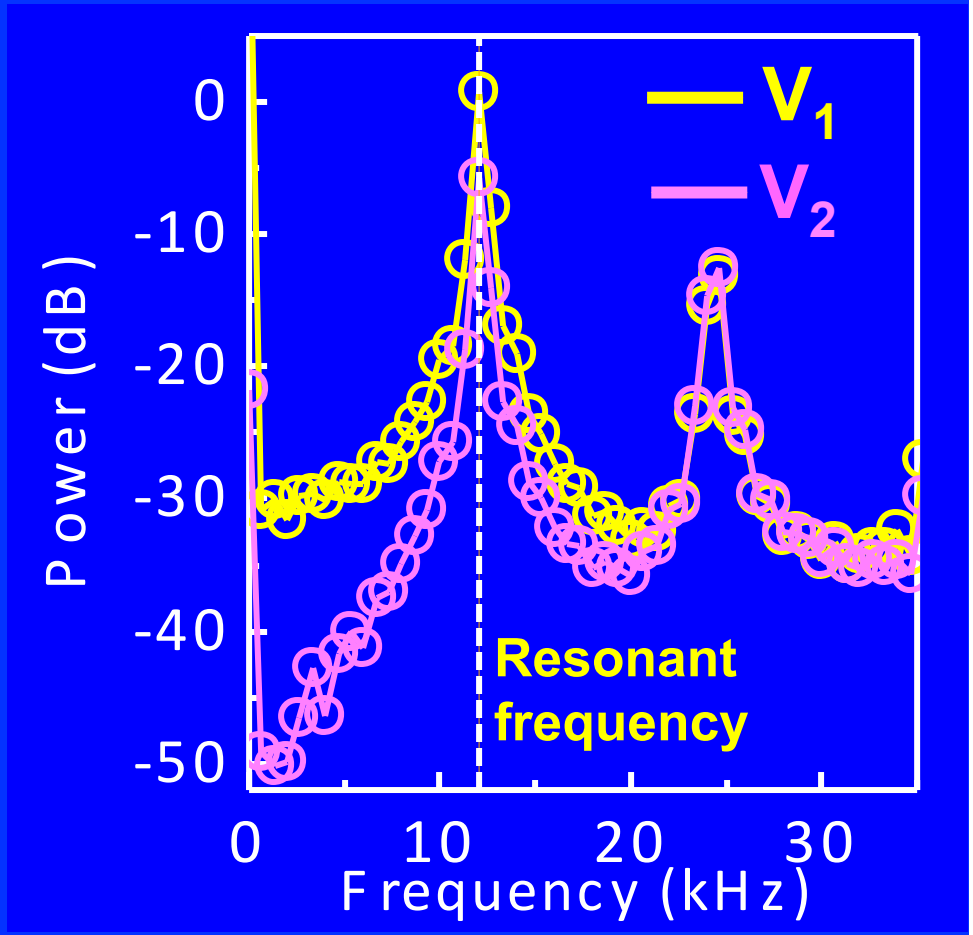
Pairwise Coupled HVFET Oscillators

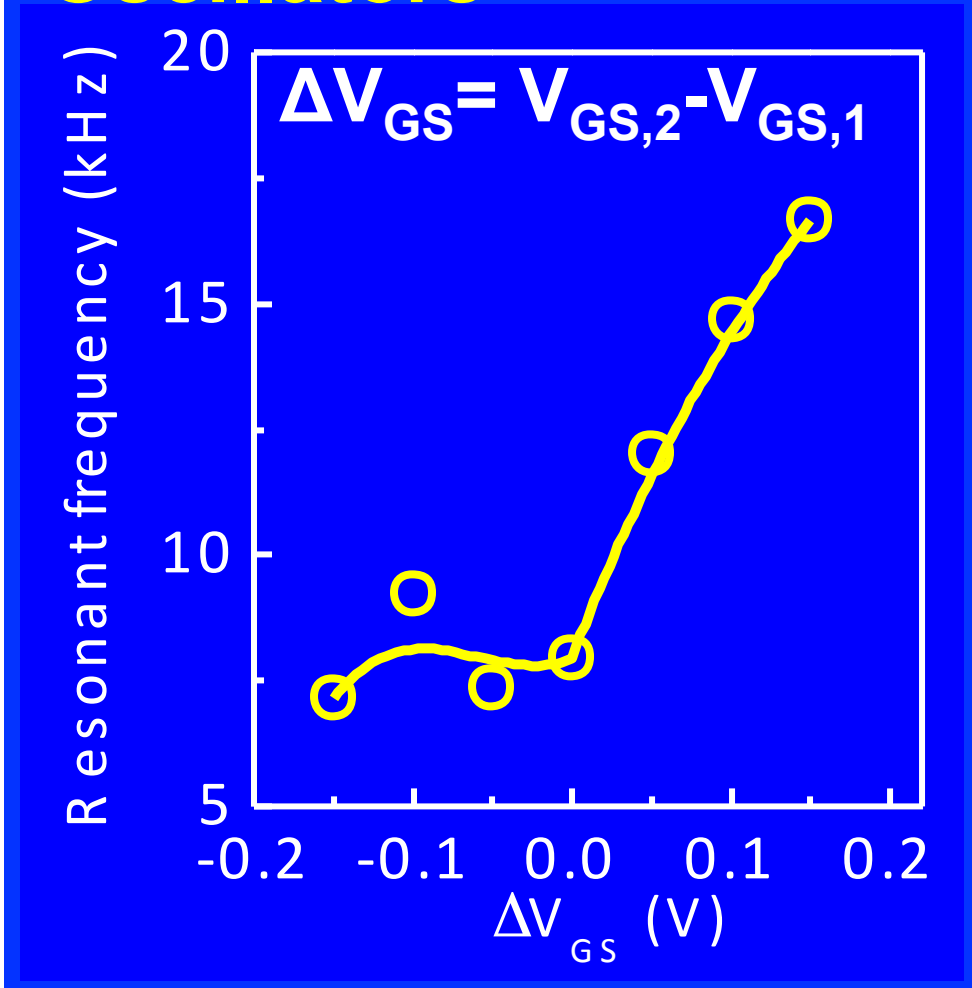


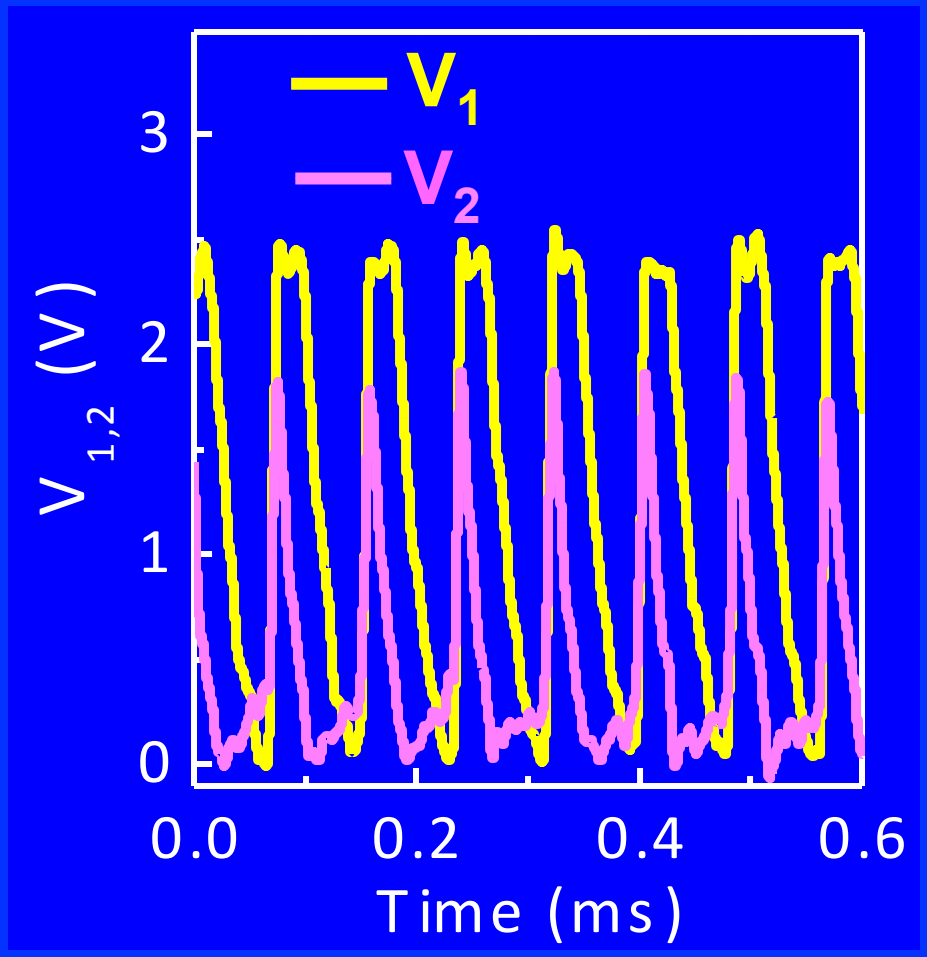
C_C= 2.2nF



➢Capacitively coupled oscillators show frequency synchronization

Synchronization of Pairwise Coupled HVFET Oscillators





- Resonant frequency can be tuned with ΔV_{GS}
- Oscillators show near anti-phase synchronization

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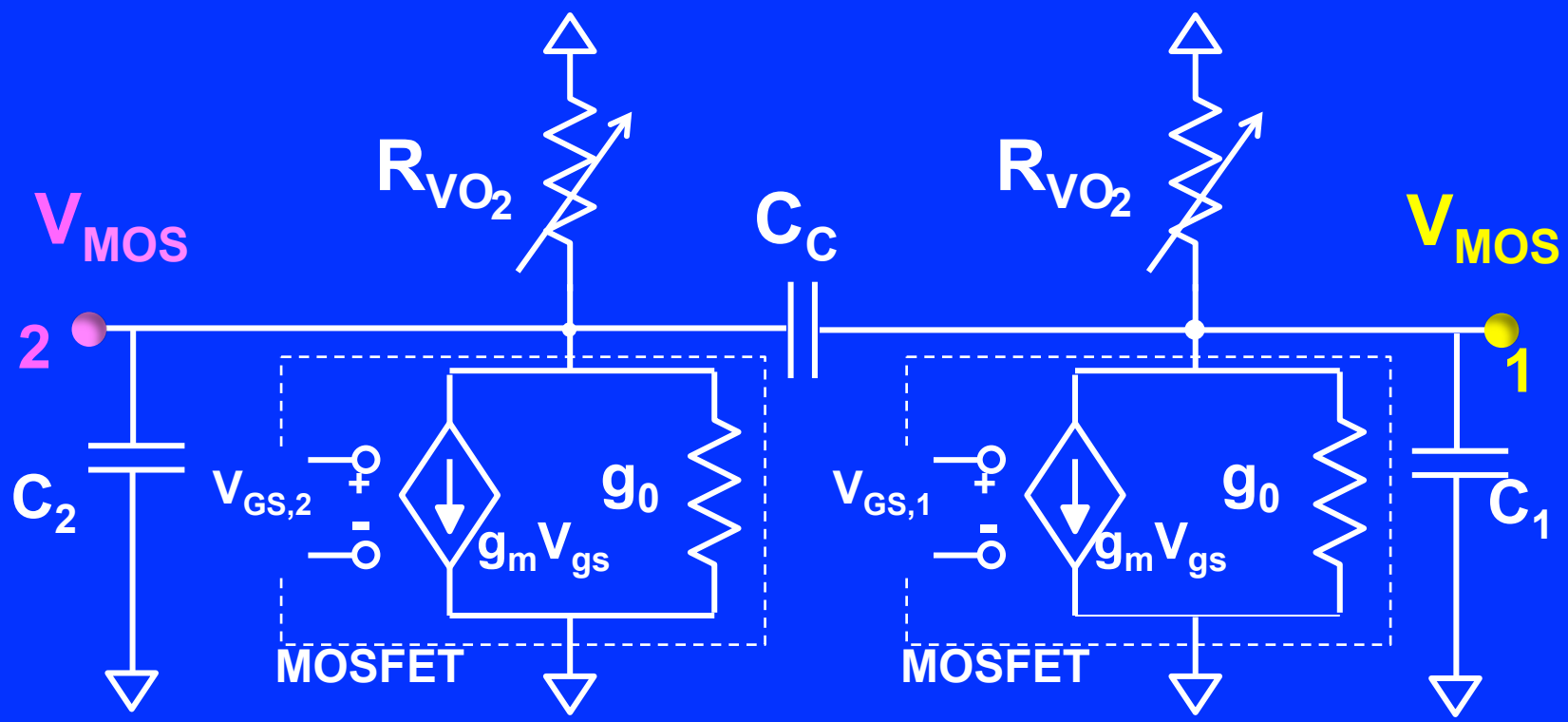
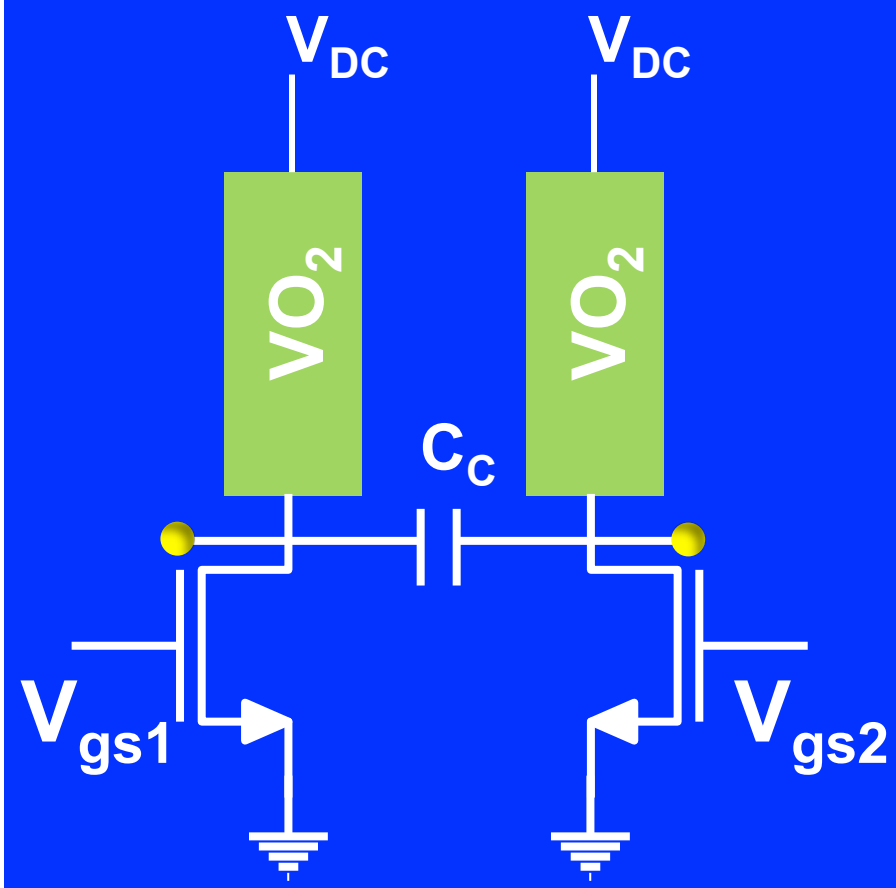
Equivalent Circuit for coupled HVFET Oscillators



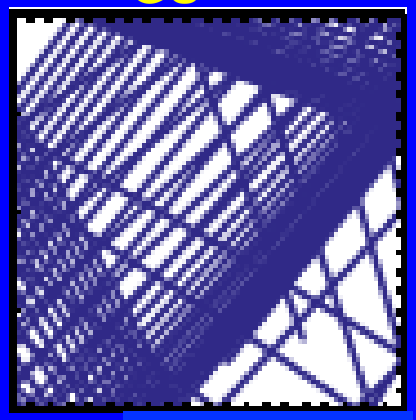
- Equivalent circuit to analyze HVFET oscillator synchronization dynamics

Phase Space Diagram (locking / unlocking)



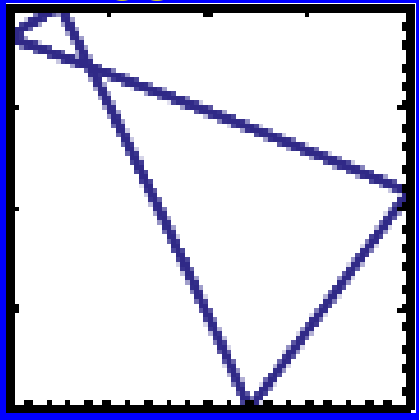
$\Delta V_{GS}=V_{GS,2}-V_{GS,1}$

ΔV_{GS}=-0.2 V



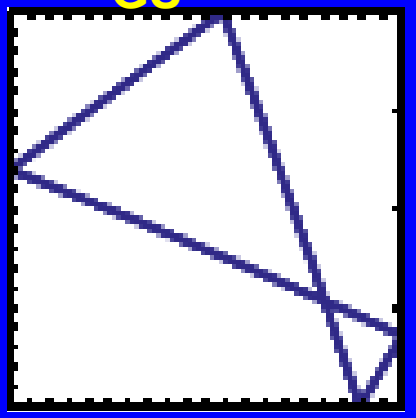
Unlocked

ΔV_{GS}=-0.02 V



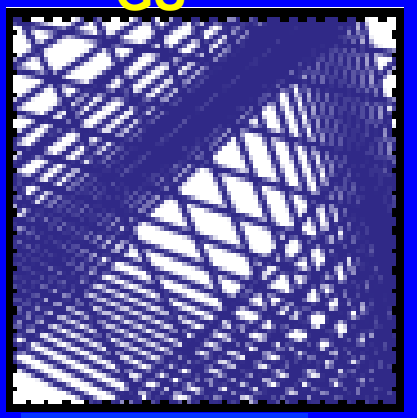
Locked

ΔV_{GS}=0.02 V



Locked

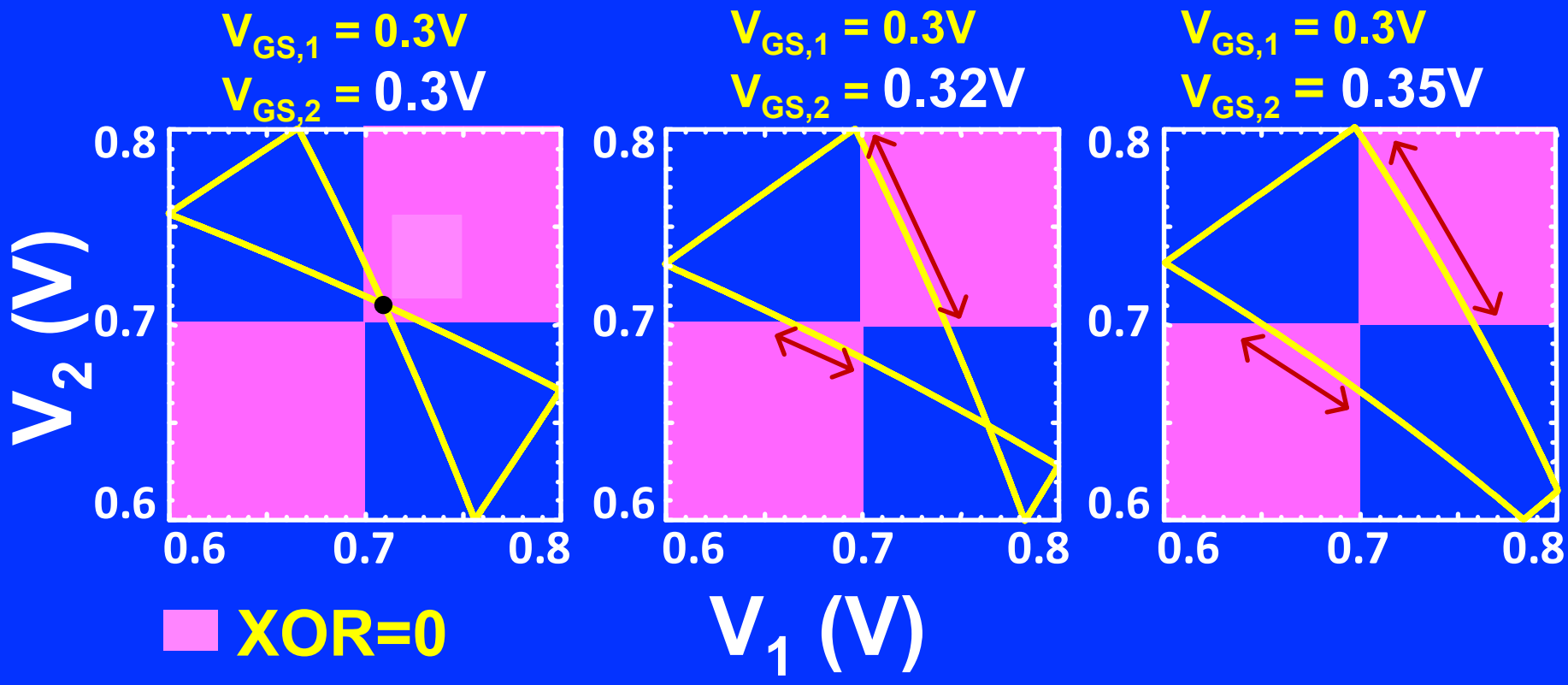
ΔV_{GS}=0.2 V



Unlocked

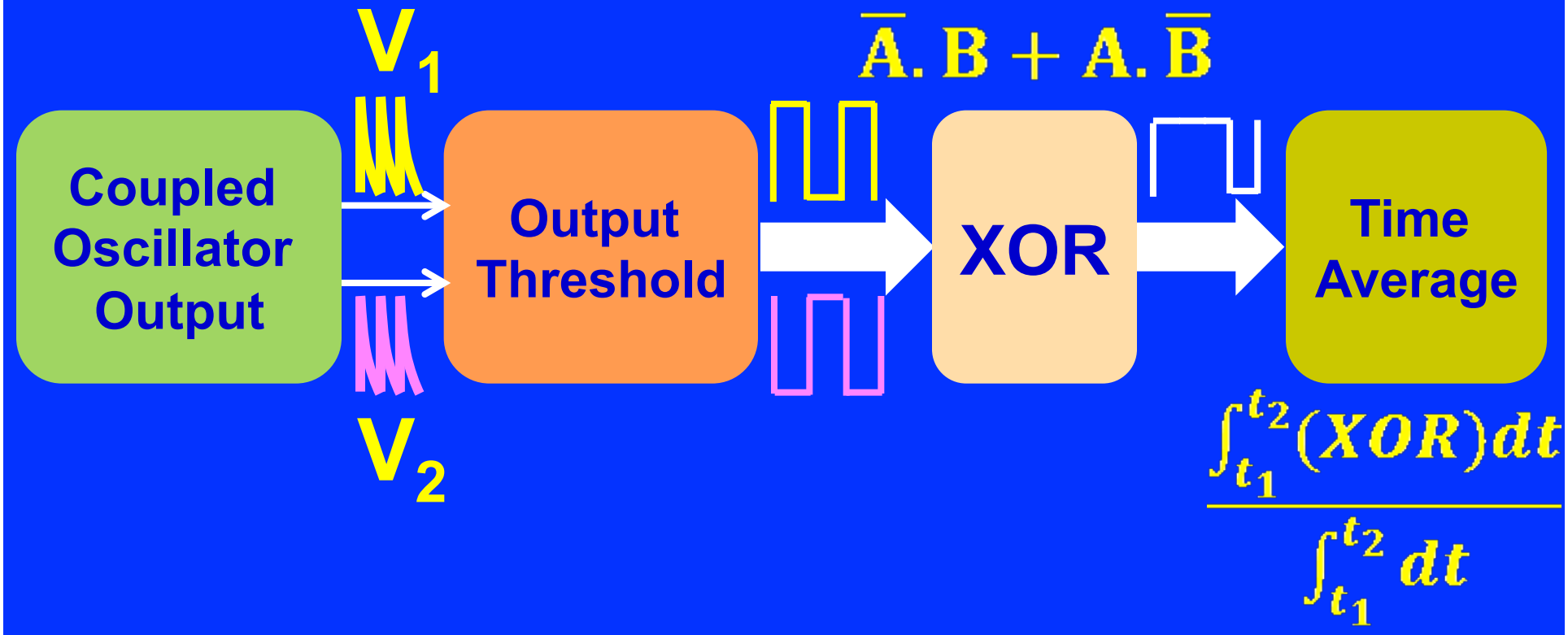
➢Gate Input voltage difference decides synchronization

Phase Space Diagram (Locked Case)



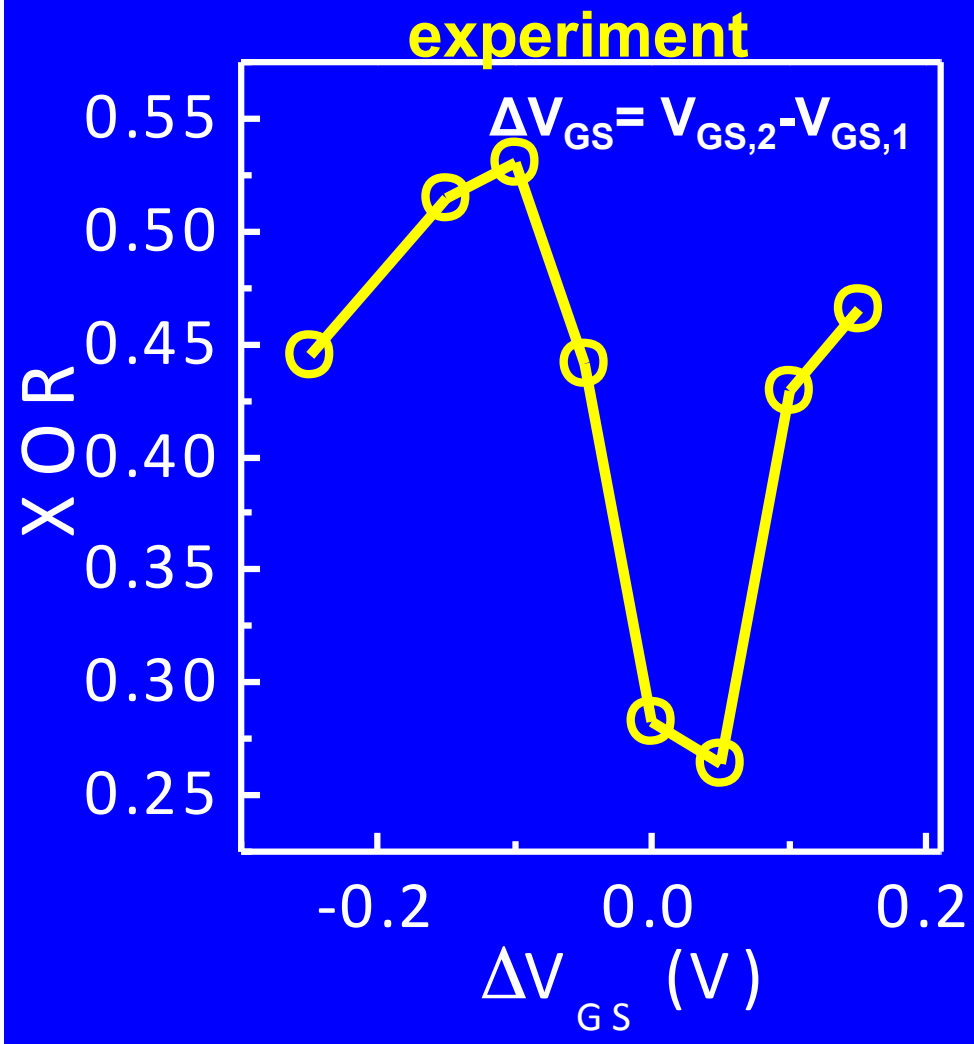
➢Part of steady state periodic orbit in the XOR=0 region of the phase space depends on $\Delta V_{GS} = V_{GS,2} - V_{GS,1}$

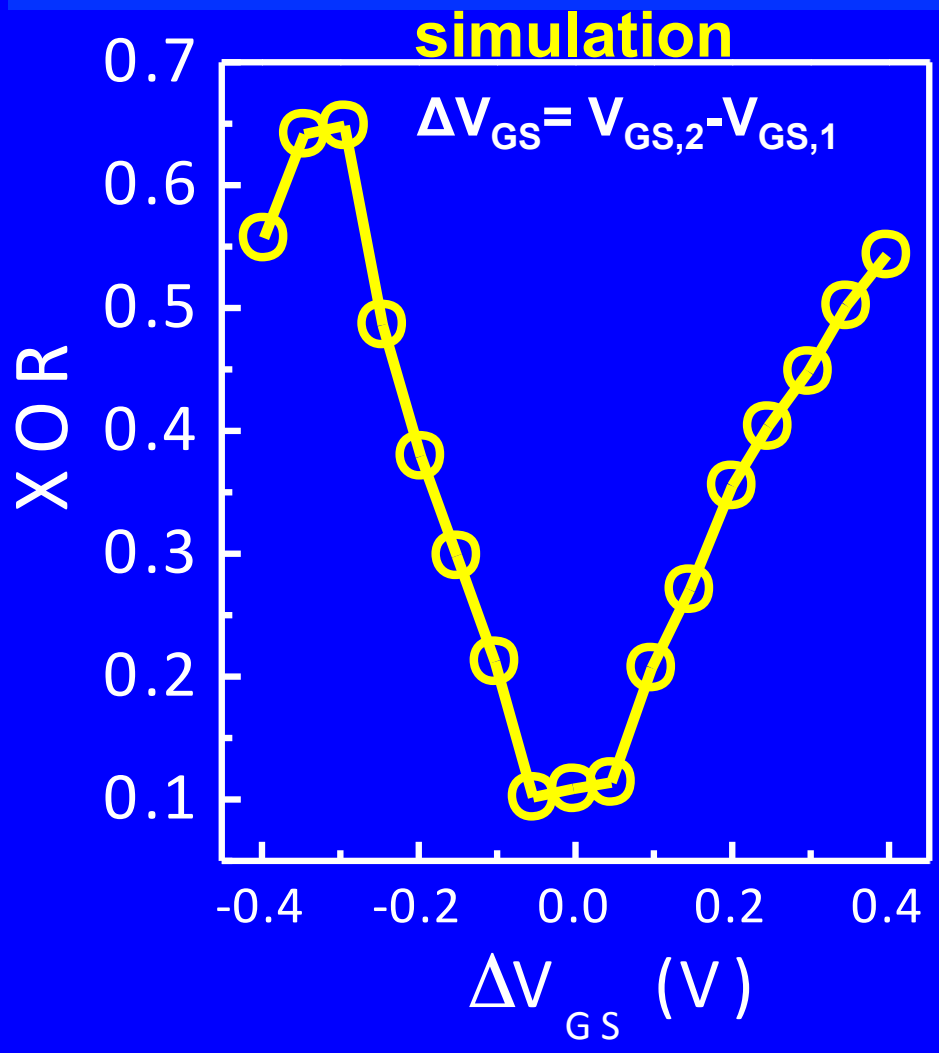
Phase Difference measurement



- System implementation to measure steady state periodic orbit of the HVFET oscillators

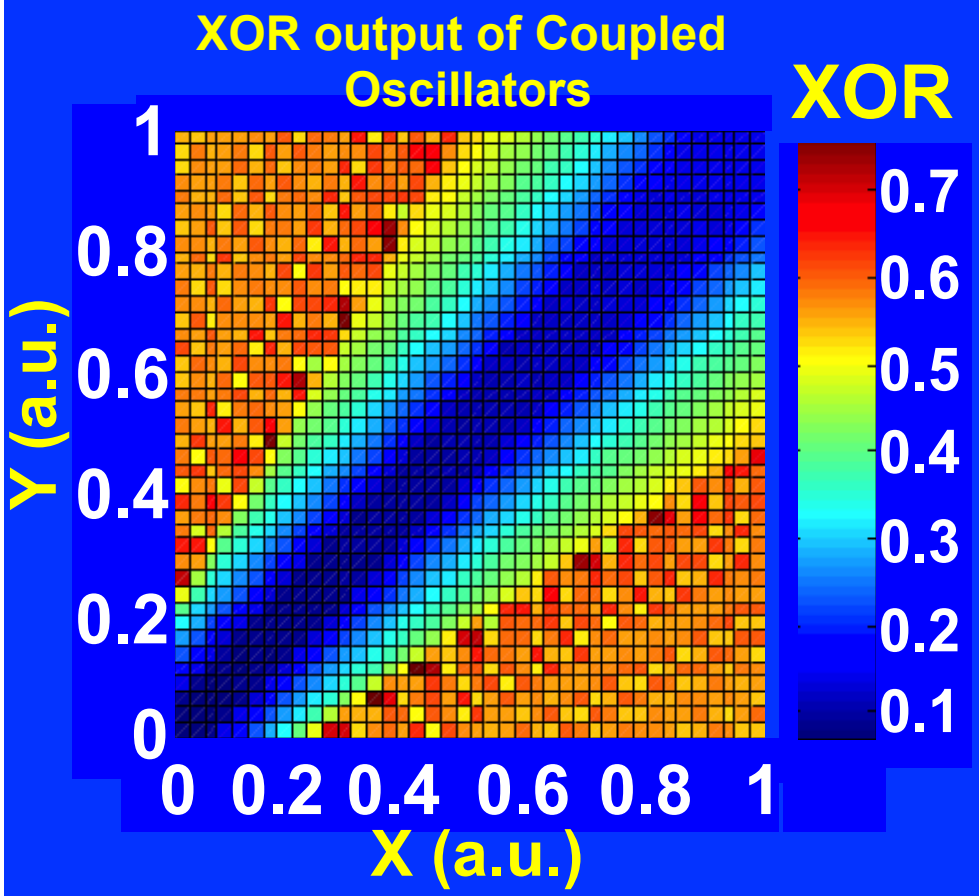
Distance calculation using Coupled HVFET oscillators

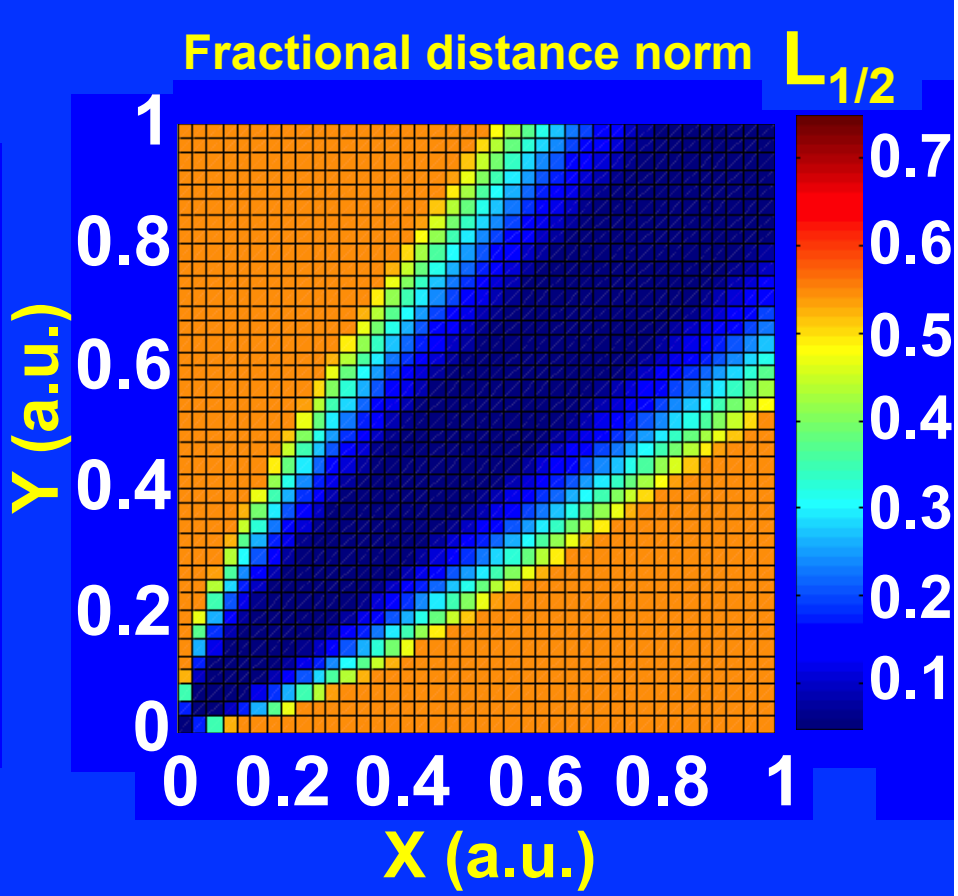




- Degree of match between inputs can be measured with HVFET oscillators

Distance Norm (L) for pairwise coupled oscillators





- Synchronized HVFET oscillators follow a $L_{1/2}$ distance norm
- Distance computing hardware realized using synchronized HVFET oscillators

Visual attention using Coupled Oscillators and CMOS

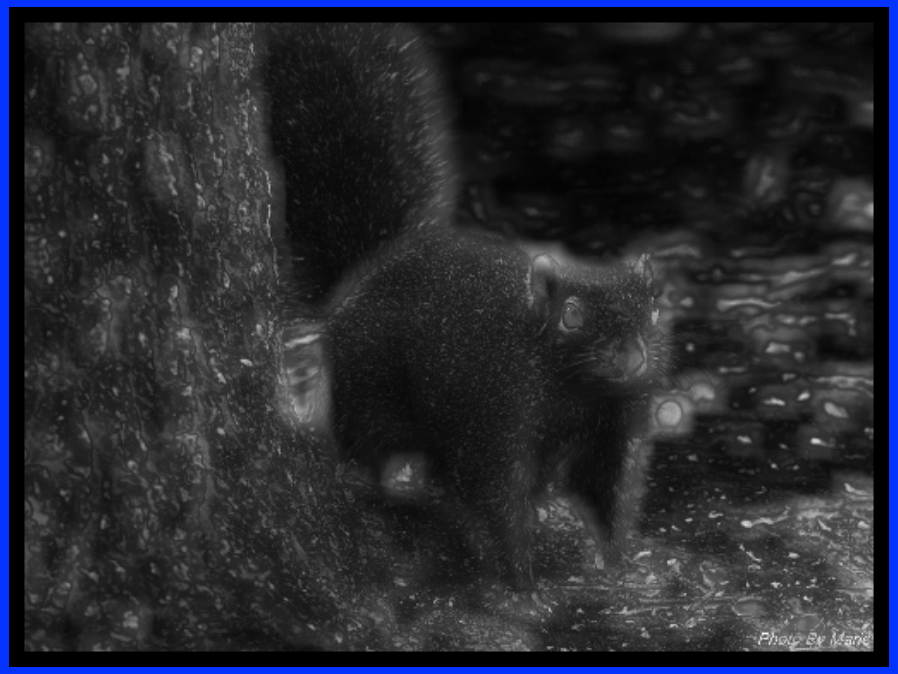
Visual Attention

- Objects with high degree of contrast most salient to human eye

Visual Saliency using Coupled Oscillators and CMOS

Coupled Oscillators

CMOS



- VO_2 coupled oscillators an alternate hardware to do visual saliency

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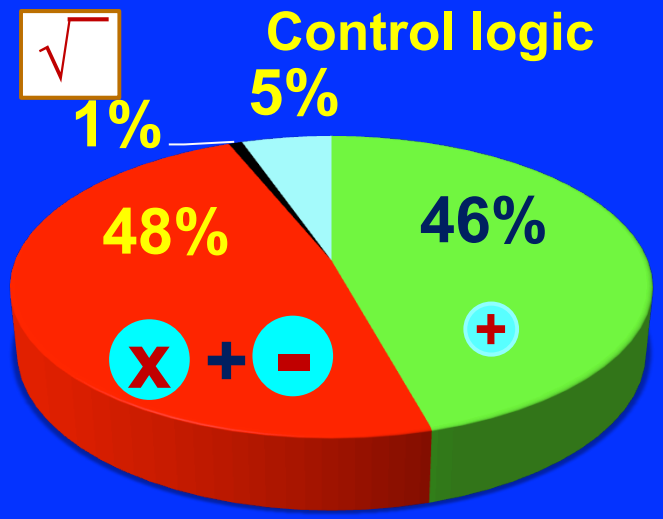
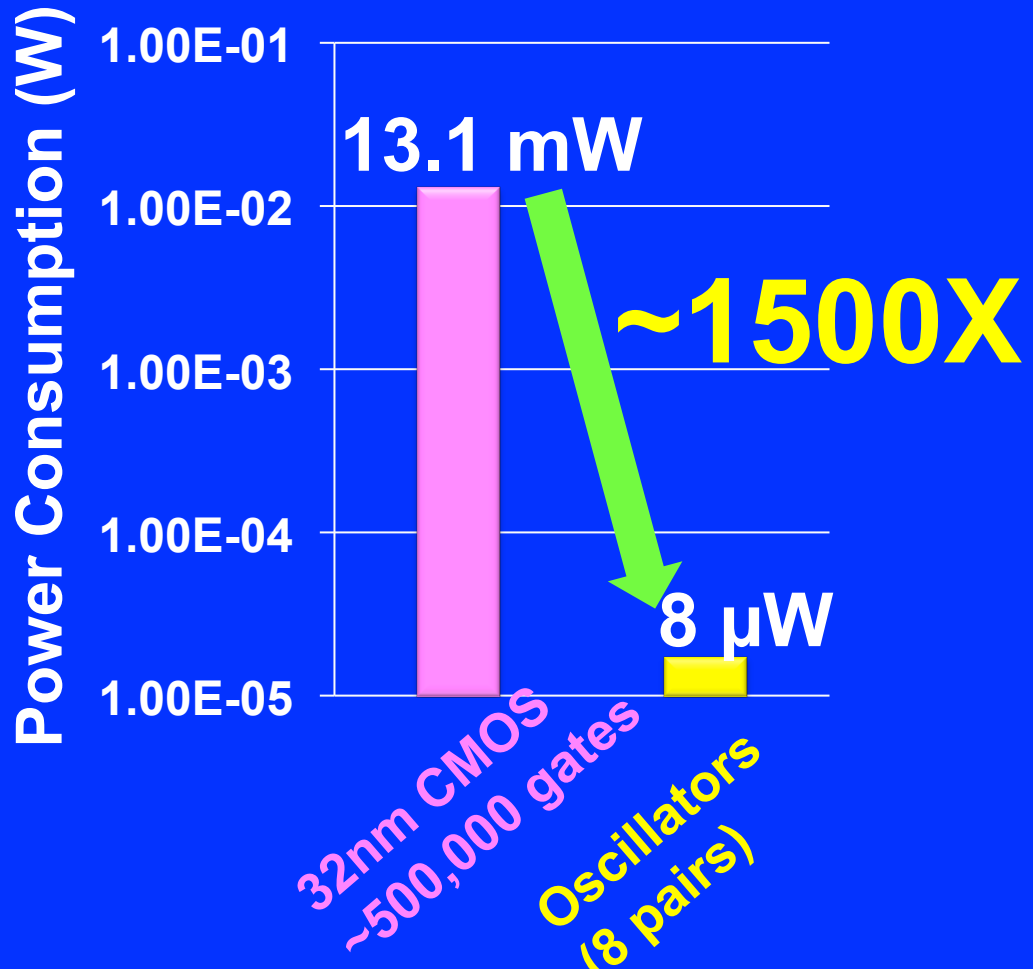
Benchmarking

CMOS based Euclidean norm

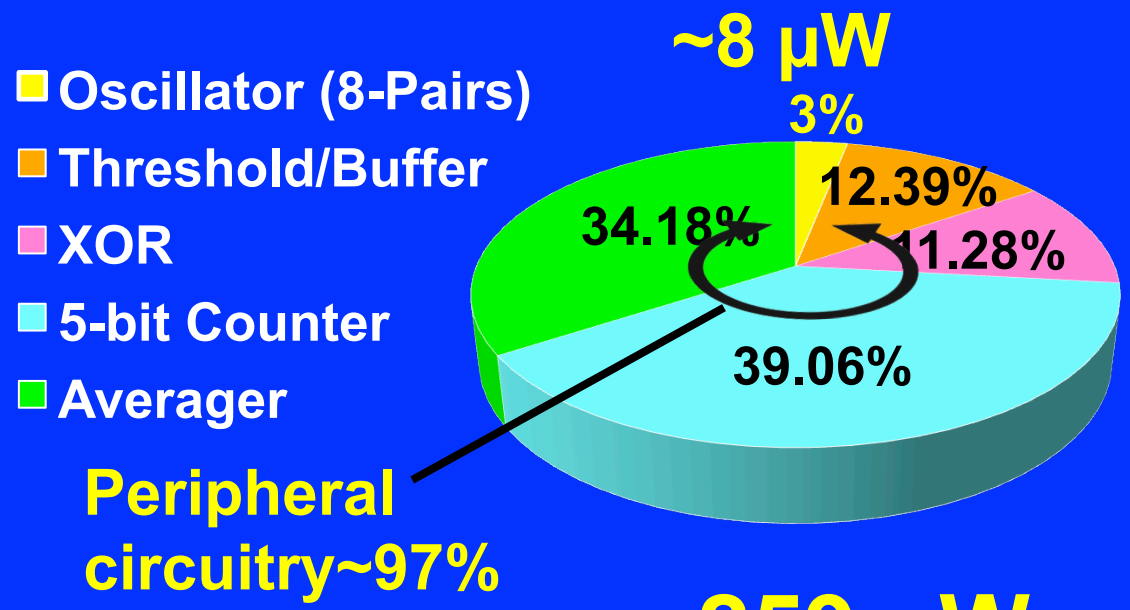


13.1mW & ~500,000 gates



- Small number of oscillators required to a compute distance norm
- Distance computing with oscillators results in ~1500X power reduction (fundamental distance computing hardware)

Power Analysis: HVFET based computational hardware

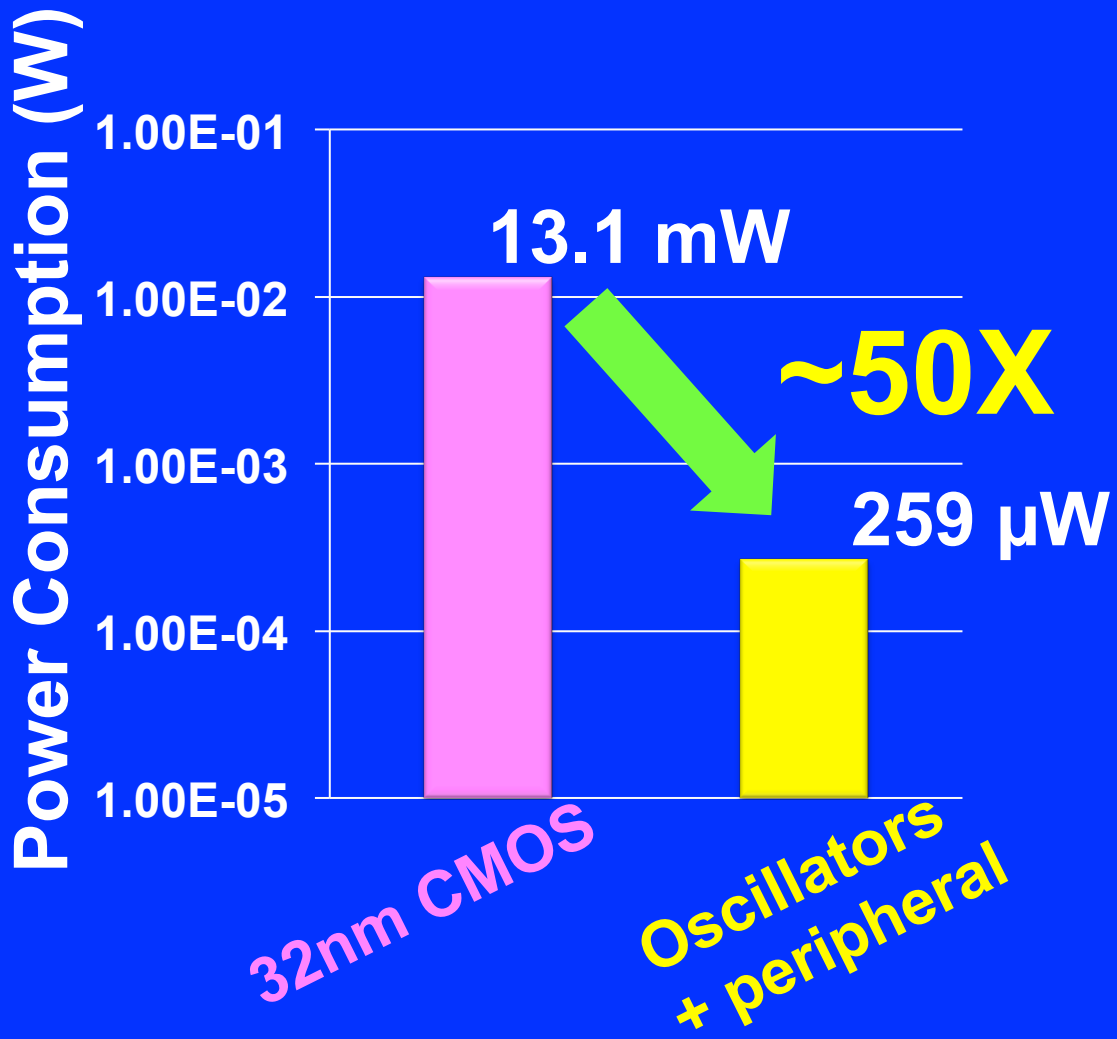


~259 µW

8 oscillators + 752 gates

- Peripheral circuitry a large power consumer

Benchmarking



➢~50X power reduction enabled through a physics based computing approach!

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Summary

- Experimental demonstration of coupled VO_2 based relaxation oscillators with input programmable synchronization
- Demonstration of coupled oscillators as a fractional distance ($L_{1/2}$) computing machine
- Application in Associative processing e.g. visual
- physics based computing approach!

Thank you!