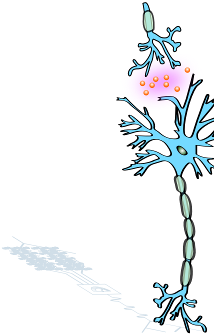
Artificial Synapses based on the Photoconductance of $LaAlO_3/SrTiO_3$ Quantum Wells



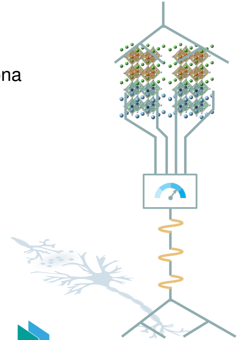
Yu CHEN

Institut de Ciència de Materials de Barcelona

(ICMAB-CSIC)

Supervisor: Dr. Gervasi HERRANZ

14th November 2019



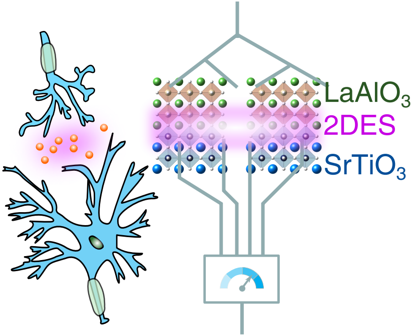
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA EXCELENCIA SEVERO OCHOA

MULFOX

Outline

1. Introduction: Neuromorphic computation
2. Methods: Fabrication and Characterization
3. Observations: Persistent Photoconductance, Photocarrier accumulation & depletion
4. Interpretation: Theoretical Models
5. Applications: Cognitive tasks in artificial network
6. Outlook and Perspectives: artificial vision
7. Conclusion

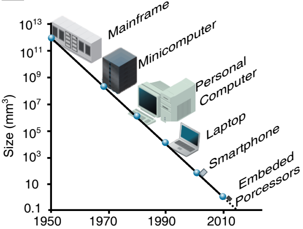
Introduction: Neuromorphic computation

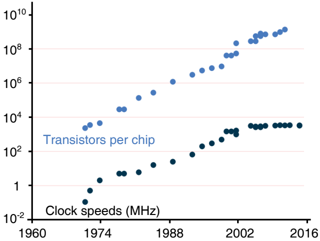


Background

CMOS Downscaling Limitations within Von Neumann architecture

M. M. Waldrop. Nature 530.7589 (2016)





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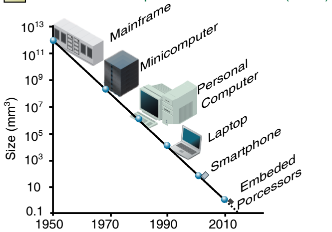

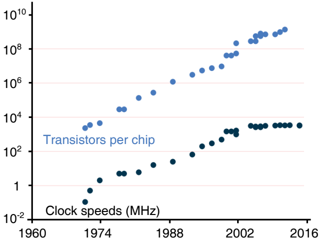

- Thermal wall

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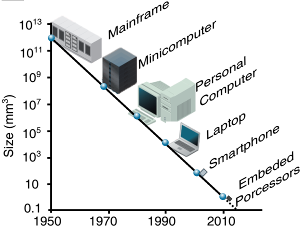

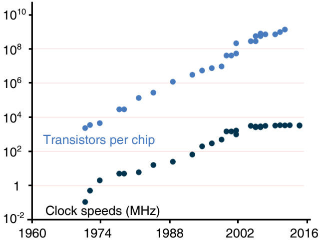

- Thermal wall
- Memory wall

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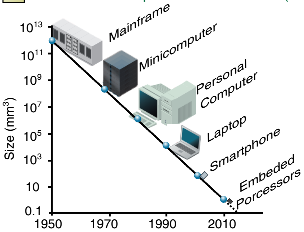

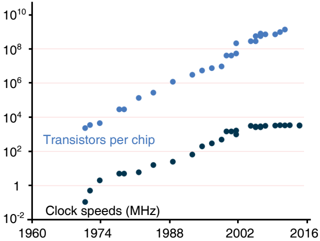

CMOS Scaling within Von Neumann architecture

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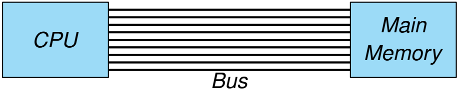

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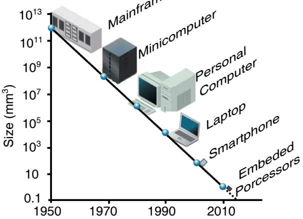
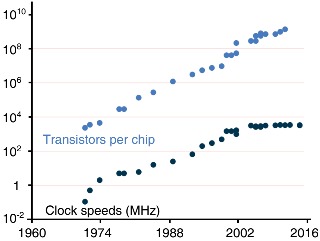
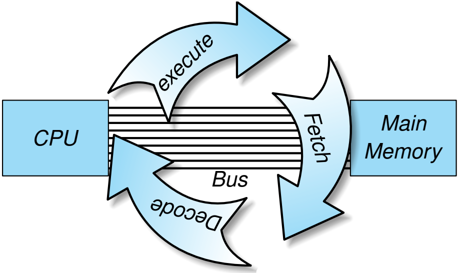




CMOS Scaling within Von Neumann architecture

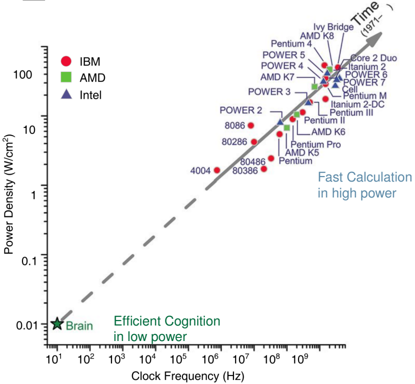
- Thermal wall
- Memory wall
  How can we overcome the Von Neumann bottleneck?



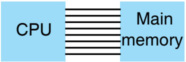
Background

Brain-inspired Neuromorphics beyond Von Neumann architecture

P. A. Merolla et al. Science 345.6197 (2014)



Sequential and centralized Von Neumann architecture of today's computer



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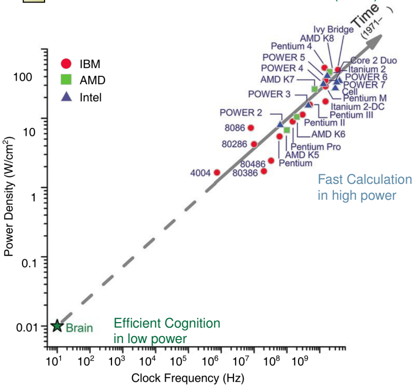

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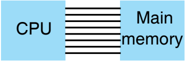

LeCun, Y. et al. Nature 521, 436444 (2015).

A woman is throwing a frisbee in a park.

A dog is standing on a hardwood floor.

A little girl sitting on a bed with a teddy bear.

A stop sign is on a road.

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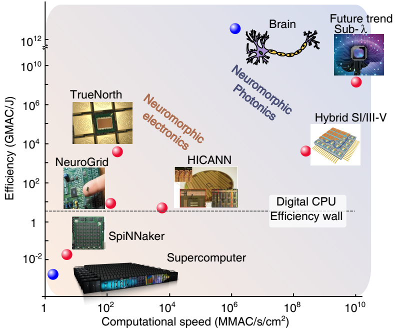
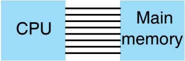
T. Ferreira de Lima et al. Nanophotonics 6.3(2017)



Neuromorphic hardware platforms based on the spiking neural networks



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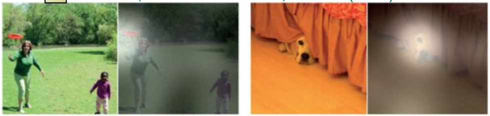

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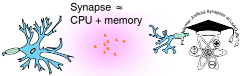

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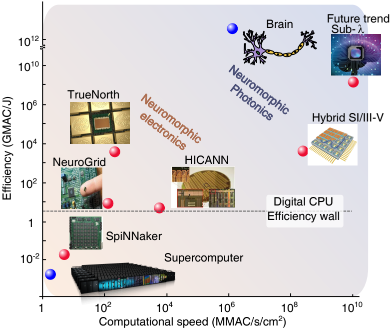

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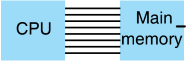
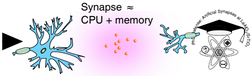


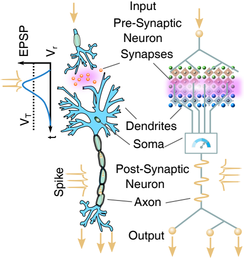
How do the Neuromorphic devices work?

Spiking Neural Networks



Spiking neural networks

Towards neuromorphic computational architectures



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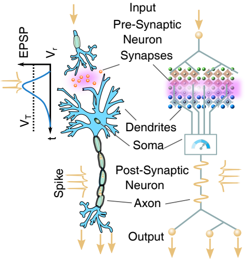
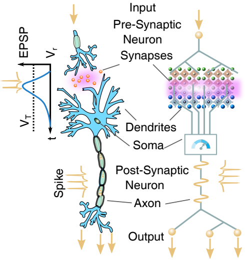


1. Synaptic plasticity

Spiking neural networks

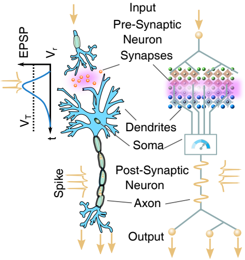
Towards neuromorphic computational architectures



1. Synaptic plasticity
2. Threshold selectivity

Spiking neural networks

Towards neuromorphic computational architectures



1. Synaptic plasticity
2. Threshold selectivity
3. Spiking programmability

Spiking neural networks

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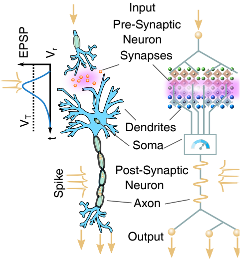
M. F. Bear et al., Neuroscience: Exploring the brain. Lippincott Williams & Wilkins 5, (2014).



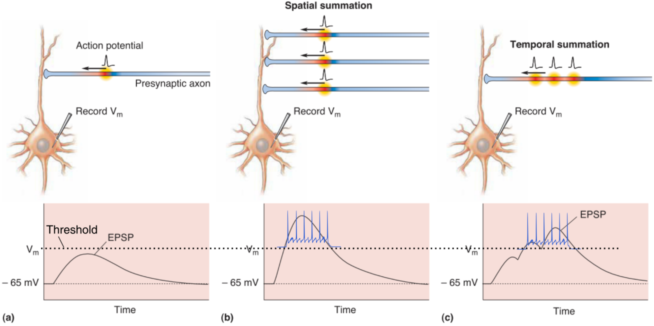


Figure: Summation of excitation postsynaptic potential (EPSP)

1. Synaptic plasticity
2. Threshold selectivity
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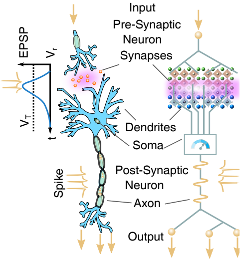

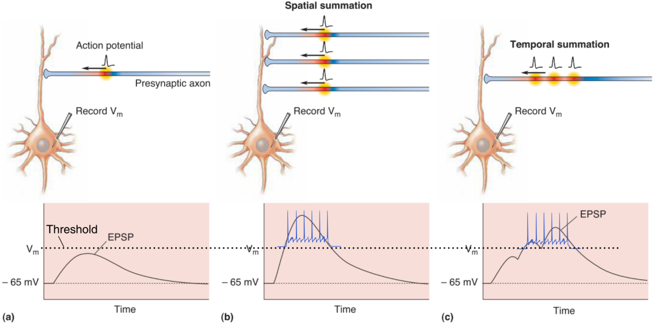

Figure: Summation of excitation postsynaptic potential (EPSP)

1. Synaptic plasticity
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4. Stimuli summability

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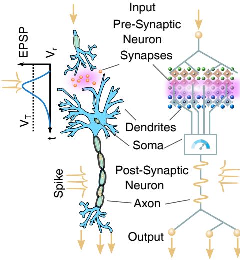

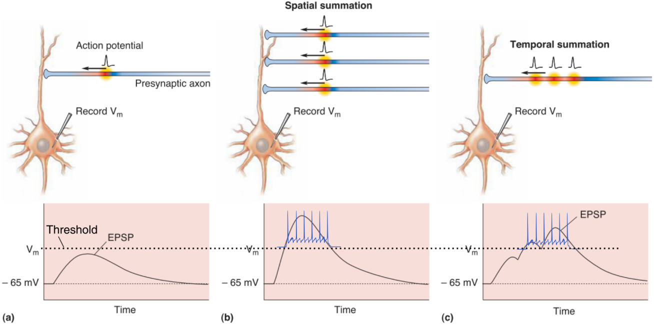

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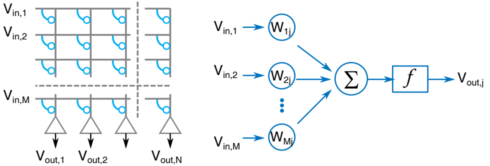

Figure: Artificial neural network and accumulating weight operation

Spiking neural networks

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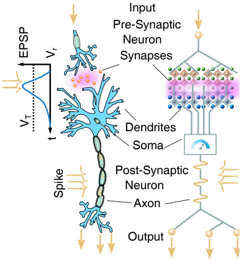

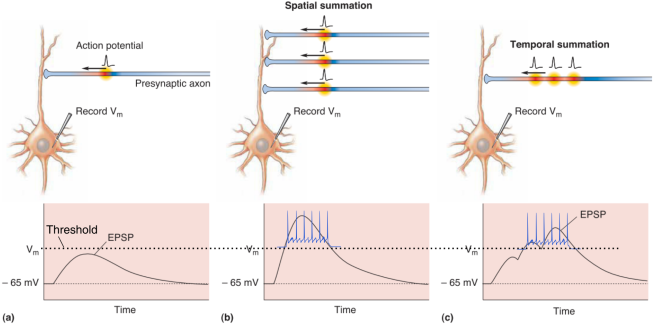

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How can synaptic plasticity be used to set learning rule?

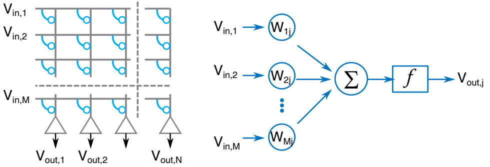
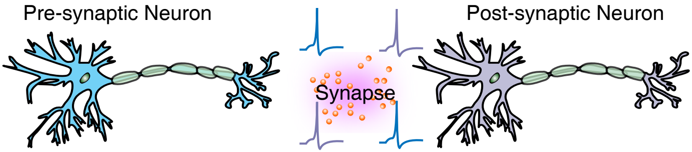
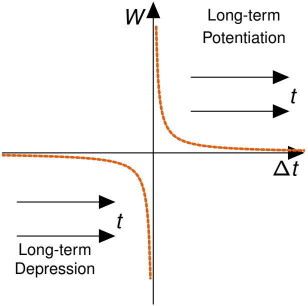


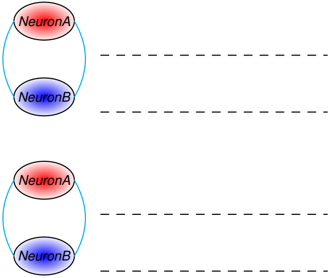
Figure: Artificial neural network and accumulating weight operation

Spike-timing dependent plasticity (**STDP**)

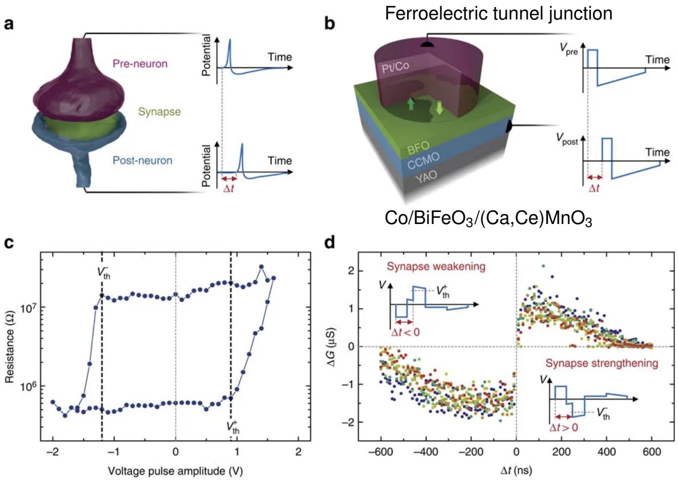
Leaning--" Timing is Everything "







STDP replication in physical systems: memristors



S. Boyn et al., Learning through ferroelectric domain dynamics in solid-state synapses, Nature Communications, 14736 (2017)

From electric stimuli to optical stimuli

Memristors: STDP with Electric Input

Achieving STDP from electric stimuli to optical stimuli?

From electric stimuli to optical stimuli

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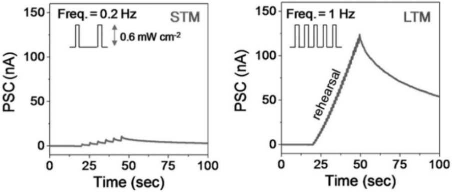
M. Lee et al. Advanced Materials 29.28 (2017)

Artificial Synapses based on Persistent Photoconductance (PPC)



Indium gallium zinc oxide (IGZO)

- Synaptic plasticity
- Cumulative response

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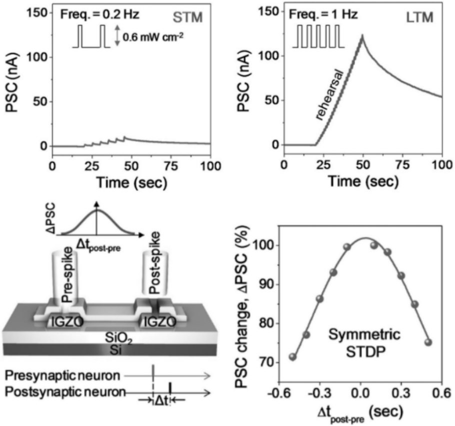

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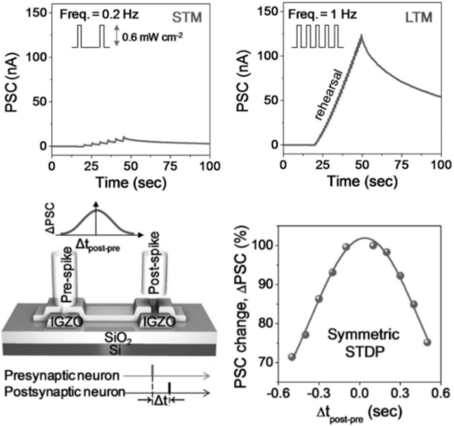

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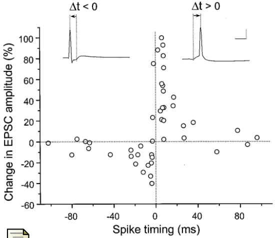

G.-q. Bi et al. The Journal of Neuroscience 18.24 (1998)

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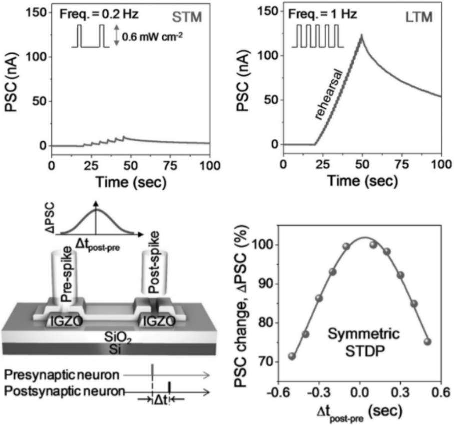

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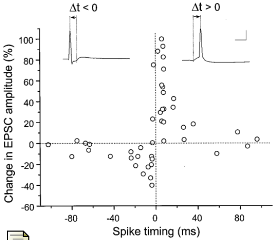

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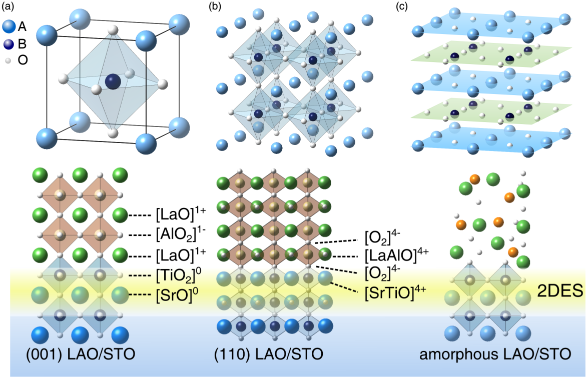
Q: Can we implement asymmetric STDP with optical input?

A: Photocarrier accumulation → **Depletion**

$LaAlO_3/SrTiO_3$ interfaces

Perovskite oxides



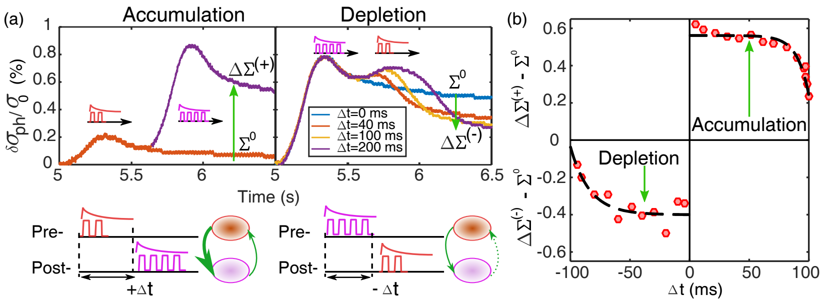
Quantum well a few unit cells thick (10 – 100Å)

- 2D Superconductivity
- Strong Rashba Spin-Orbit fields
- Persistent Photoconductance (PPC)

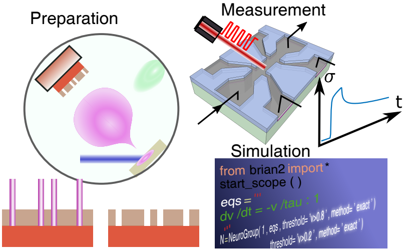
Asymmetric Persistent Photoconductance

Wavelength-dependent time-correlated photoresponse

Excitatory and inhibitory synapses with optic inputs

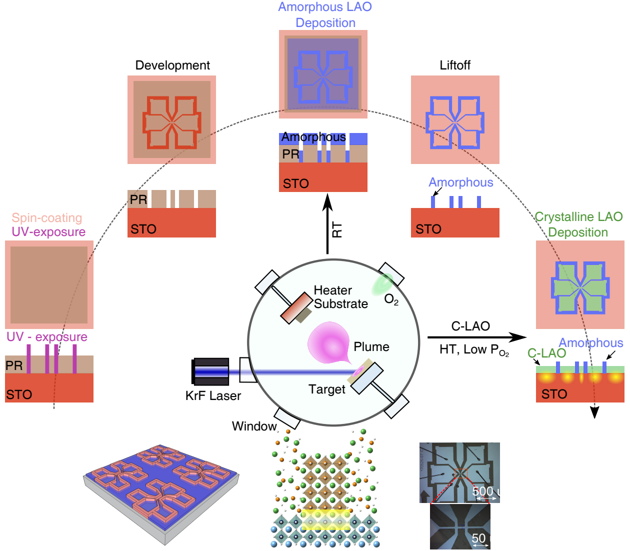


Methods: Fabrication and Characterization

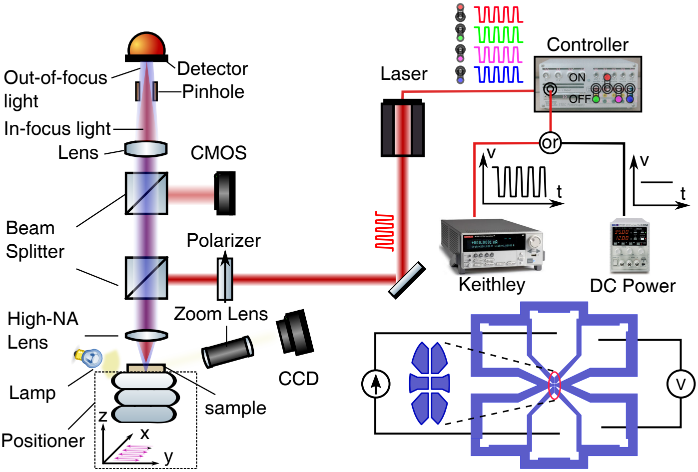


Sample Fabrications

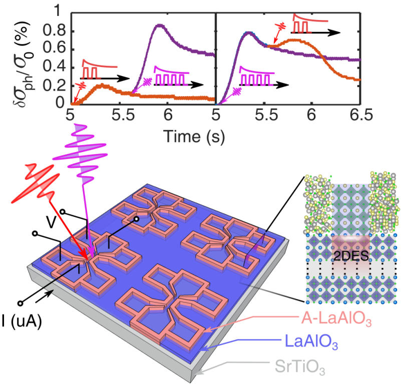
Optical lithography and pulsed laser deposition (PLD)



Electric Transport Measurements under illumination

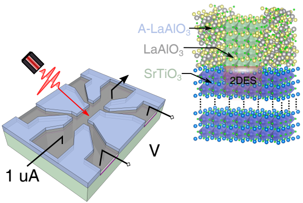


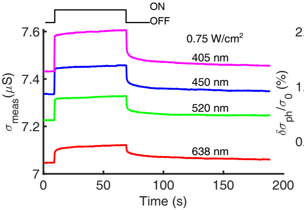
Observations: Persistent Photoconductance, Photocarrier accumulation & depletion

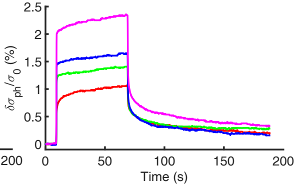


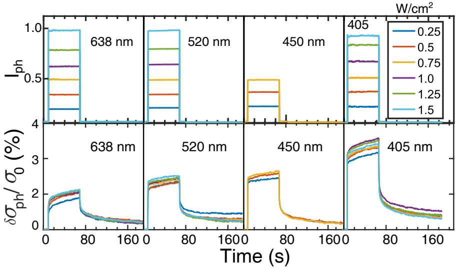
Persistent Photoconductance (PPC)

depends on the wavelength and Light power density







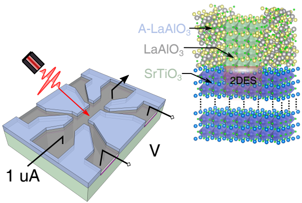


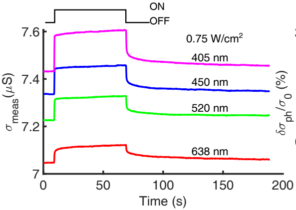
Response to single pulse with timescale of seconds

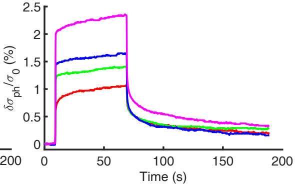
- Wavelength
- Light power density

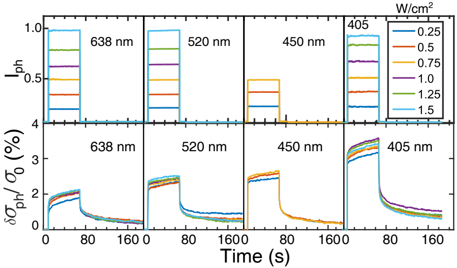
Persistent Photoconductance (PPC)

depends on the wavelength and Light power density









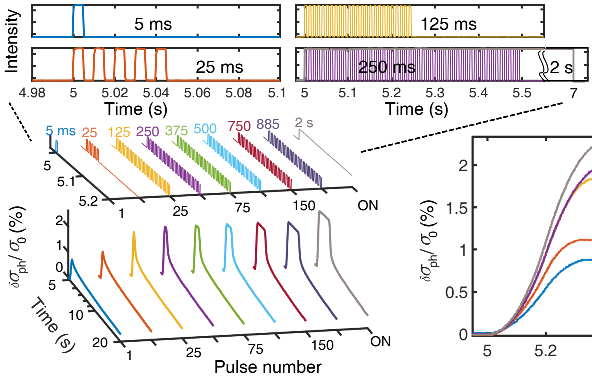
Response to single pulse with timescale of seconds

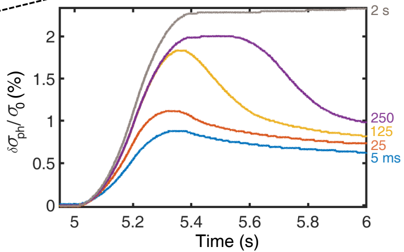
- Wavelength
- Light power density

Plasticity: Modulation with illumination cumulated time of multiple pulses

Plastic PPC depending on the cumulated time

under illumination with violet ($\lambda = 405nm$) light pulses

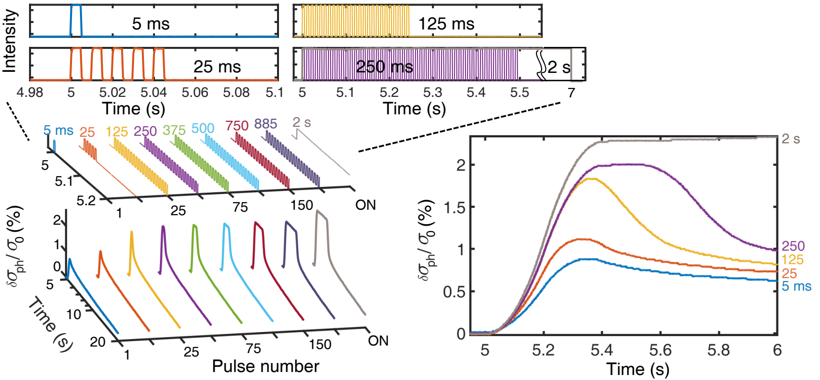




Plasticity in cumulated time → Photo-induced **Accumulation**:

Plastic PPC depending on the cumulated time

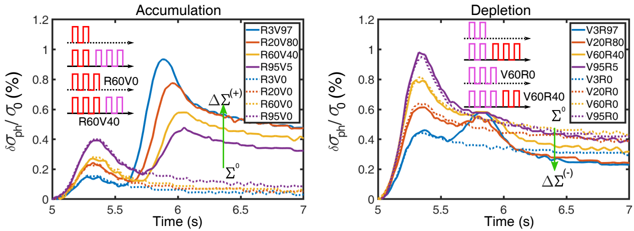
under illumination with violet ($\lambda = 405nm$) light pulses



Plasticity in cumulated time $\rightarrow$ Photo-induced **Accumulation**:
How can we achieve the **Depletion**?

Asymmetric photoresponse

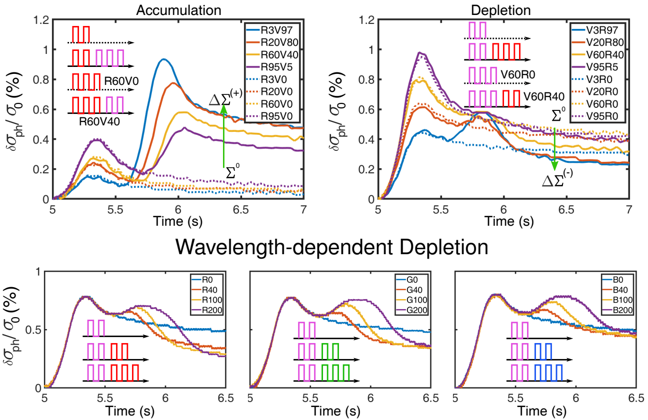
to a pair of pulses with shot-& long- wavelength



- Plasticity modulated with Cumulated time
- Time order of optical pulses matters

Asymmetric photoresponse

to a pair of pulses with shot-& long- wavelength



- Plasticity modulated with Cumulated time
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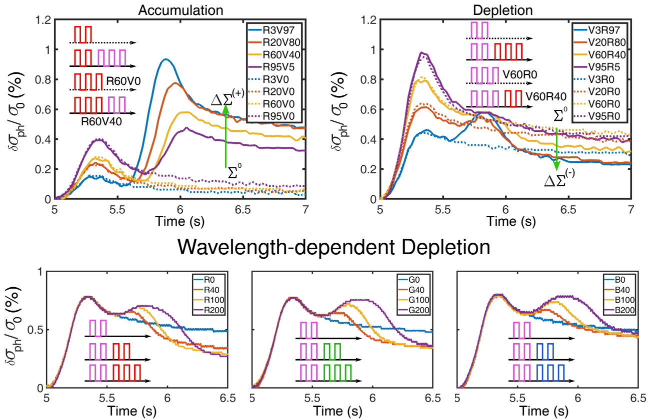
Asymmetric photoresponse

to a pair of pulses with shot-& long- wavelength

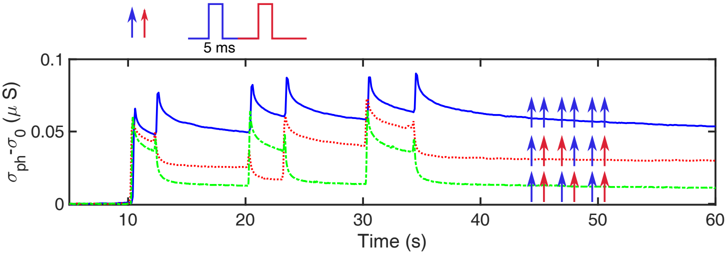


- Plasticity modulated with Cumulated time
- Time order of optical pulses matters

A pair of pulses of Long- and short wavelength → Several pairs of pulses?

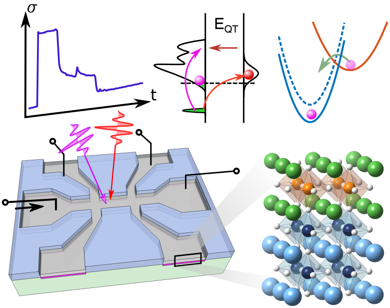
Wavelength-sensitive STDP Plasticity

through pairs of optical pulses



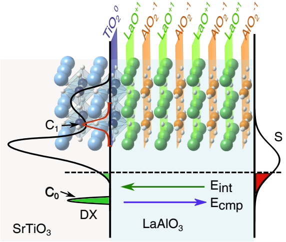
- Time order matters
- Excitatory and inhibitory synapses

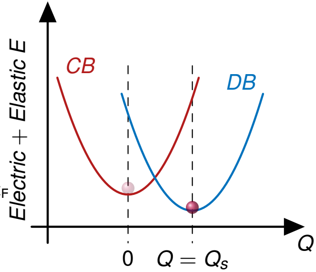
Interpretation: Theoretical Models

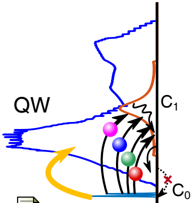


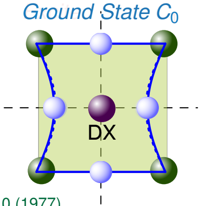
Photoinduced tunable carrier accumulation

Photo-excitation process, DX center, Large-lattice relaxation model [1,2]









The relevant Density of State (DOS):

Quantum well (QW): Linear combination of atomic orbitals (LCAO) model[3] + Wedge model [4]

DX Ground state (C_0): Deep-level transient spectroscopy (DLTS, Dr. Laurence Mechin @ CNRS - GREYC Caen)

DX excited state (C_1): Fano-Anderson model [5].

[1] D. V. Lang et al.Phys. Rev. L 39.10 (1977)

[2] C. H. Henry et al. Phys. Rev. B 15.2 (1977)

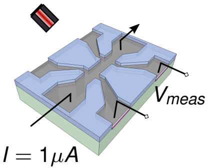
[3] T. Wolfram et al. Electronic and Optical Properties of D -Band Perovskites. Cambridge University Press, 2006.

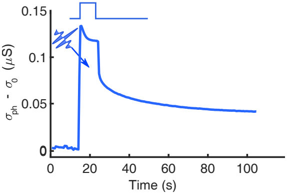
[4] A. F. Santander-Syro et al. Nature 469.7329 (2011)

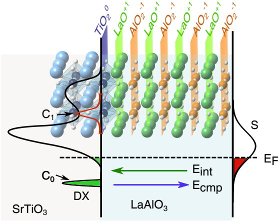
[5] G. D. Mahan. Many-particle physics. Springer Science (2013).

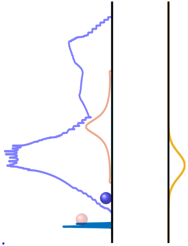
Photoinduced tunable carrier depletion

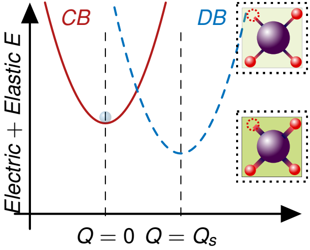
Quantum tunneling assisted by long-wavelength











Photoinduced tunable carrier depletion

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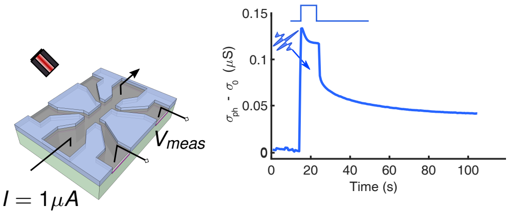
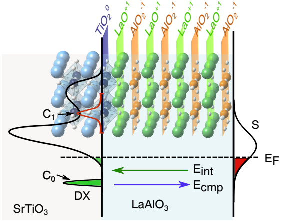
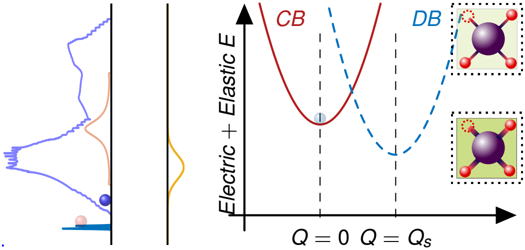
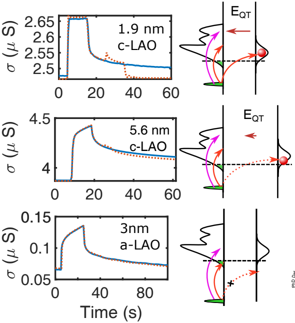
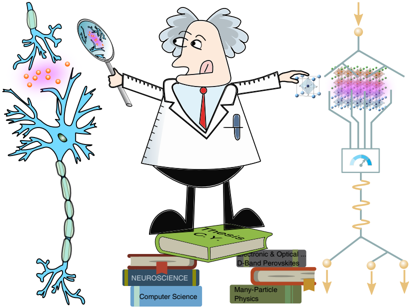




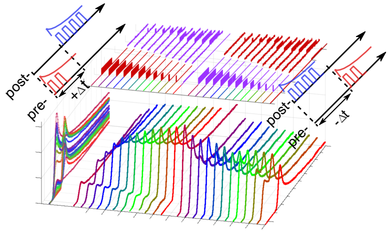


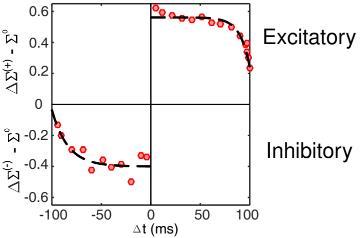


Applications: Cognitive tasks in artificial network

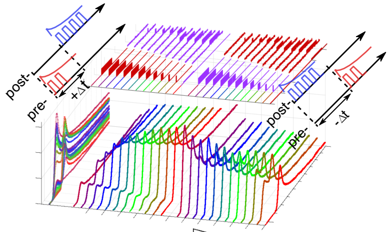


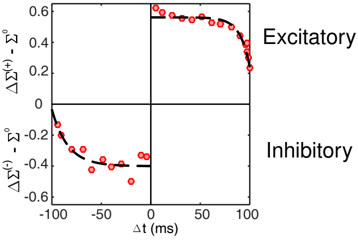
Unsupervised learning based on STDP



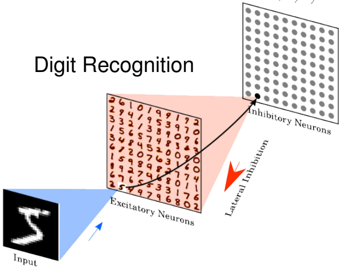


Unsupervised learning based on STDP





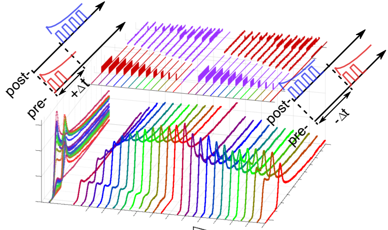
Digit Recognition

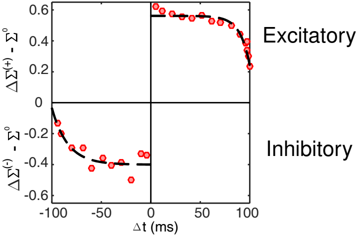


Diehl, P. U. et al. Front. Comput. Neurosci. 9, 19 (2015)

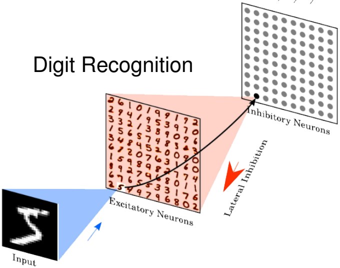
@ Institute of Neuroinformatics, ETH Zurich

Unsupervised learning based on STDP

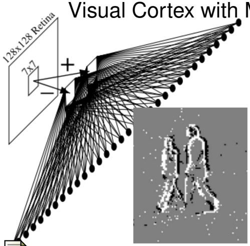




Digit Recognition



Visual Cortex with Memristors

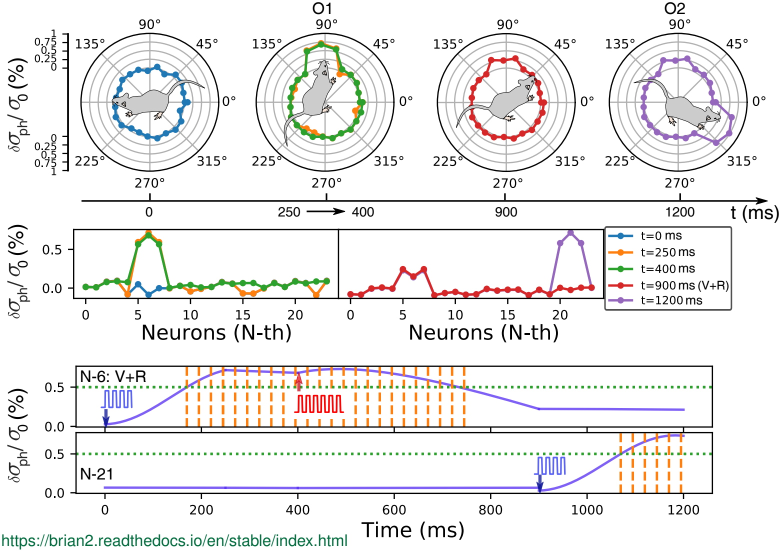


Diehl, P. U. et al. Front. Comput. Neurosci. 9, 19 (2015) @ Institute of Neuroinformatics, ETH Zurich

Zamarreño-Ramos, C. et al. Front. Neurosci. 5, 122 (2011) @ IMSE-CNM-CSIC, Sevilla

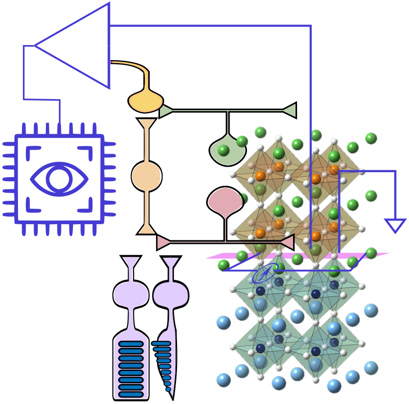
Cognitive Map Simulated by Brian Simulator

Attractor map model for head direction



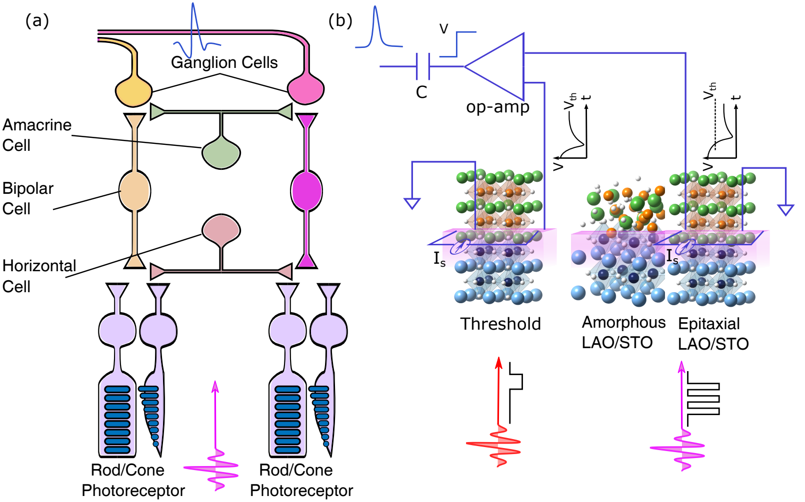
https://brian2.readthedocs.io/en/stable/index.html

Outlook and Perspectives: artificial vision

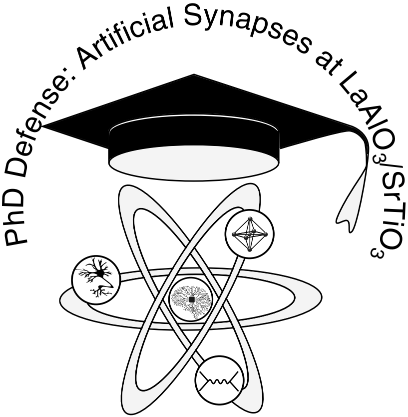


Towards optical neurons

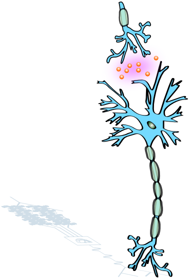
Artificial vision inspired by retina

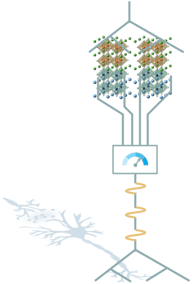


Conclusion



The Ending, The Beginning...





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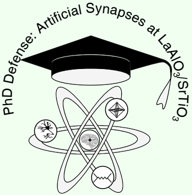

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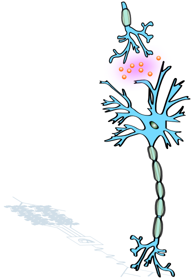
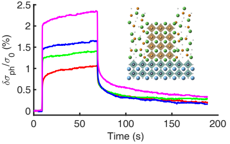
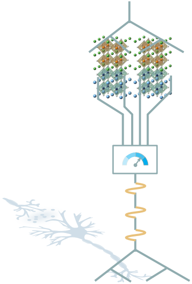


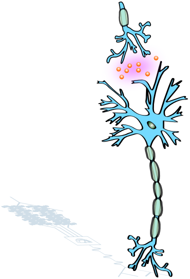


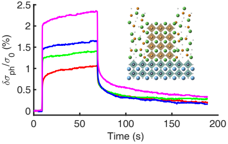


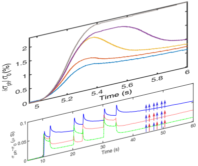
Conclusion

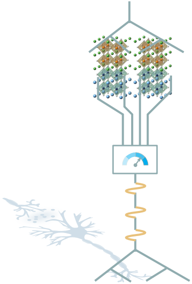
- Persistent photoconductance of epitaxial $LaAlO_3/SrTiO_3$

The Ending, The Beginning...









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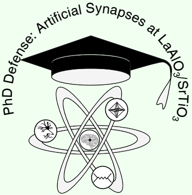
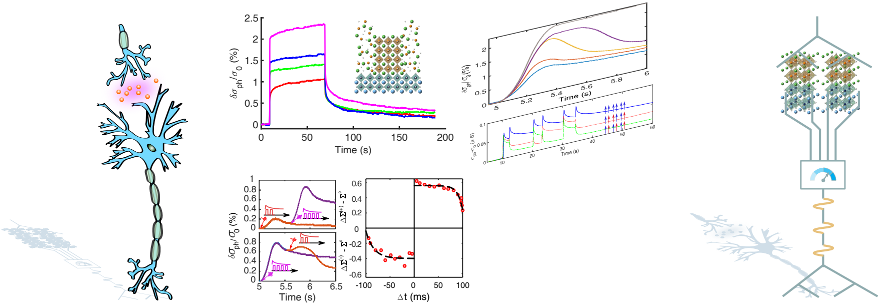
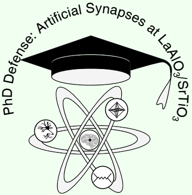


- Persistent photoconductance of epitaxial $LaAlO_3/SrTiO_3$
- Plastic PPC modulated by wavelength, power density, illumination cumulated time, pairs of short-/long-wavelength pulses

The Ending, The Beginning...



Conclusion



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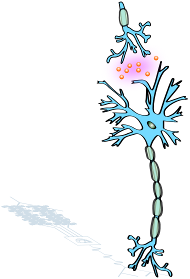

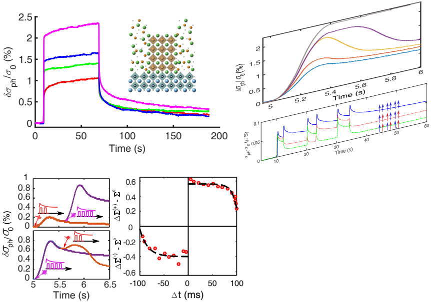

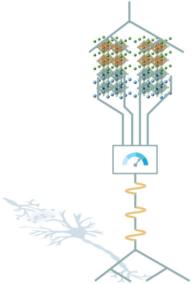

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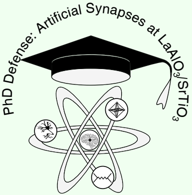

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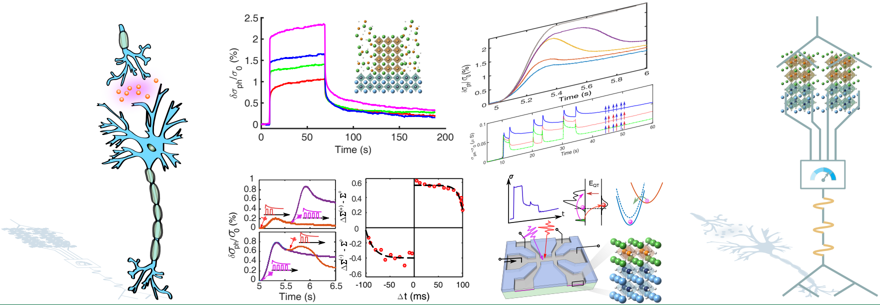

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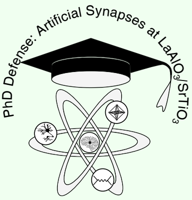

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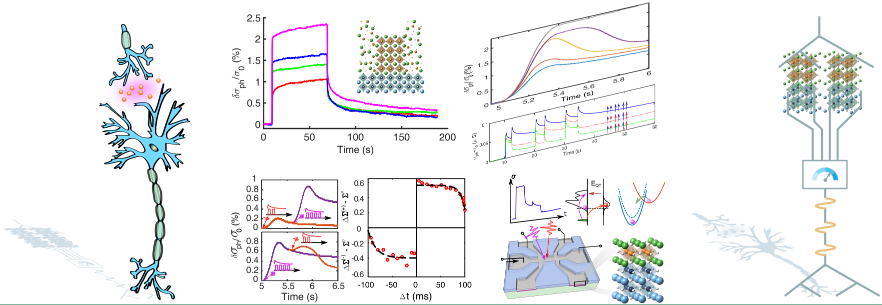
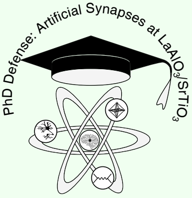


Conclusion



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- Artificial synapses with Optical STDP
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- Physical model: DX-centers, Photoexcitation, Quantum tunneling
- Applications: Cognitive task, Artificial vision

Acknowledgement

Supporting Organizations

- CSC
- ICMAB
- MULFOX group

Amazing Group mates

- Dr.Vassil Skumryev, Dr. Nico Dix, Dr. Fanmao Liu, Dr. Mendi Qian, Dr. Jike Lyu, Dr. Mateusz Ścigaj
- Yunwei Sheng, Xiao Long, Tingfeng Song, Jiahui Jia, Huan Tan
- Saúl Estandía, Mathieu Mirjolet, Milena Sulzbach
- ...

Main Collaborations

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- PLD Growth: Dr. Florencio Sánchez, Raúl Solanas
- Training & discussions: Dr. Blai Casals, Dr. Rafael Cichelero, Dr. Mikko Kataja
- Scientific benefits: Prof. Josep Fontcuberta, Dr. Ignasi Fina
- Collaborations: Dr. Laurence Mechin (CNRS - GREYC Caen, Deep-Level Transient Spectroscopy), Dr. Mariona Coll (ALD), Dr. Jaume Gazquez (STEM), Dr. Bernat Bozzo Closas (Hall-effect)

Technical support

- Cleanroom: Luigi Morrone, Marta Gerbolés Gibert, Marta Riba
- XRD: Anna Crespi