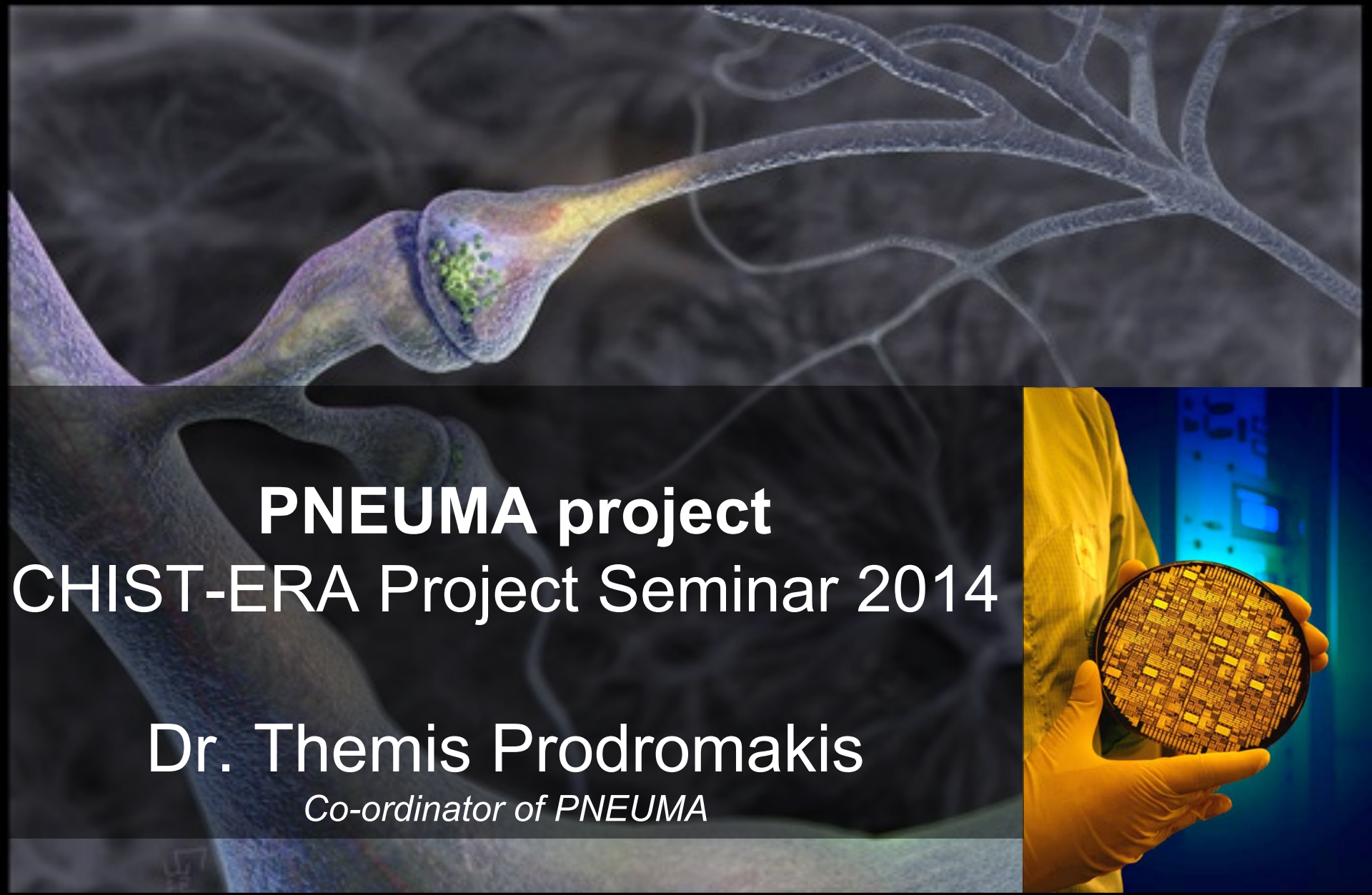




PNEUMA project

CHIST-ERA Project Seminar 2014

Dr. Themis Prodromakis

Co-ordinator of PNEUMA



Plasticity in NEUral Memristive Architectures
Istanbul, March 4th 2014



SWISS NATIONAL SCIENCE FOUNDATION

PNEUMA Aims

CHIST-ERA 1st Call – Beyond Autonomic Systems – the Challenge of Consciousness

Research approach

Philosophers, psychologists, cognitive scientists, clinicians and neuroscientists have strived to provide authoritative **definitions of consciousness** within a neurobiological framework.

Engineers have more recently joined this quest by developing **neuromorphic VLSI circuits for emulating biological functions**.

Lack of artificial systems to recreate attributes such as **true processing locality and complexity** (10^{10} synapses per cm^2).

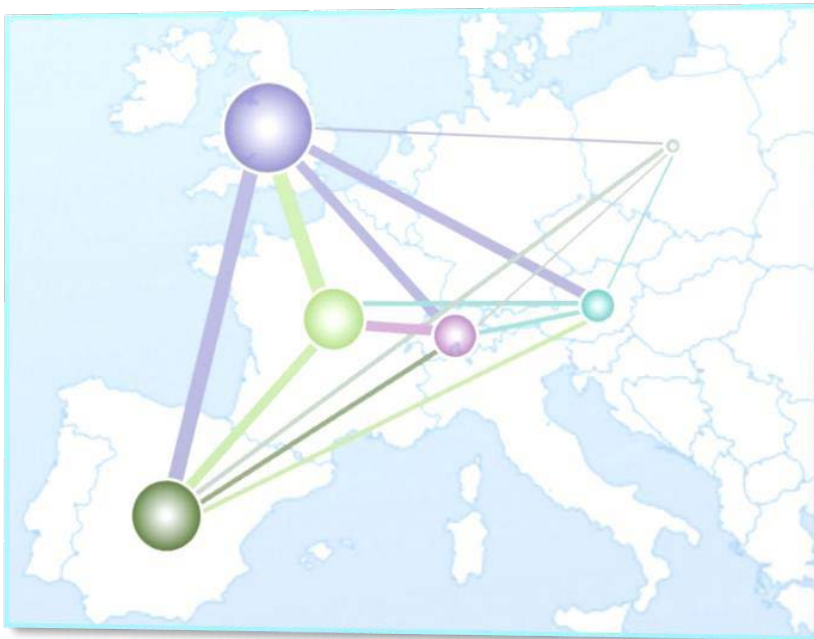
*This project aspires to **develop experimental platforms capable of perceiving, learning and adapting** to stimuli by leveraging on the latest developments of five leading European institutions in **neuroscience, nanotechnology, modeling and circuit design**. The non-linear dynamics as well as the plasticity of the newly discovered memristor are shown to support Spike-based- and Spike-Timing-Dependent-Plasticity (STDP), making this extremely compact device an excellent candidate for **realizing large-scale self-adaptive circuits; a step towards “autonomous cognitive systems”**. The intrinsic properties of real neurons and synapses as well as their organization in forming neural circuits will be exploited for optimizing CMOS-based neurons, memristive grids and the integration of the two into real time biophysically realistic neuromorphic systems. Finally, the platforms would be tested with conventional as well as abstract methods to evaluate the technology and its autonomous capacity.*



chist-era

PNEUMA partnership

Geographical Distribution



EPSRC
Engineering and Physical Sciences
Research Council

AGENCE NATIONALE DE LA RECHERCHE
ANR

FWF

Der Wissenschaftsfonds.



FNRS

SWISS NATIONAL SCIENCE FOUNDATION

Institutions

**Imperial College
London**

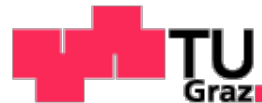
Centre for Bio-Inspired Technology



**institute of
neuroinformatics**



**University of
Zurich**
UZH



Group Leaders

Dr. Themis Prodromakis

Prof. Bernabe Linares-Barranco

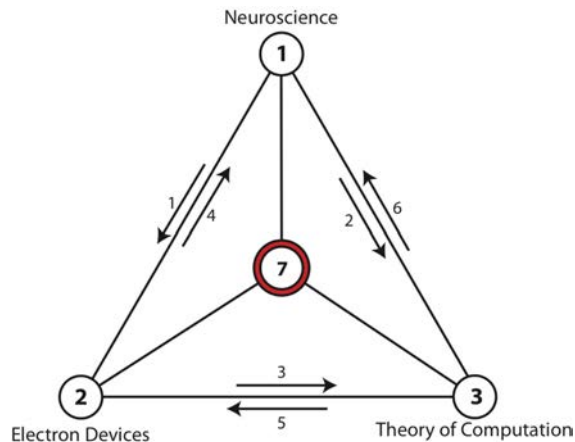
Dr. Giacomo Indiveri

Dr. Robert Legenstein

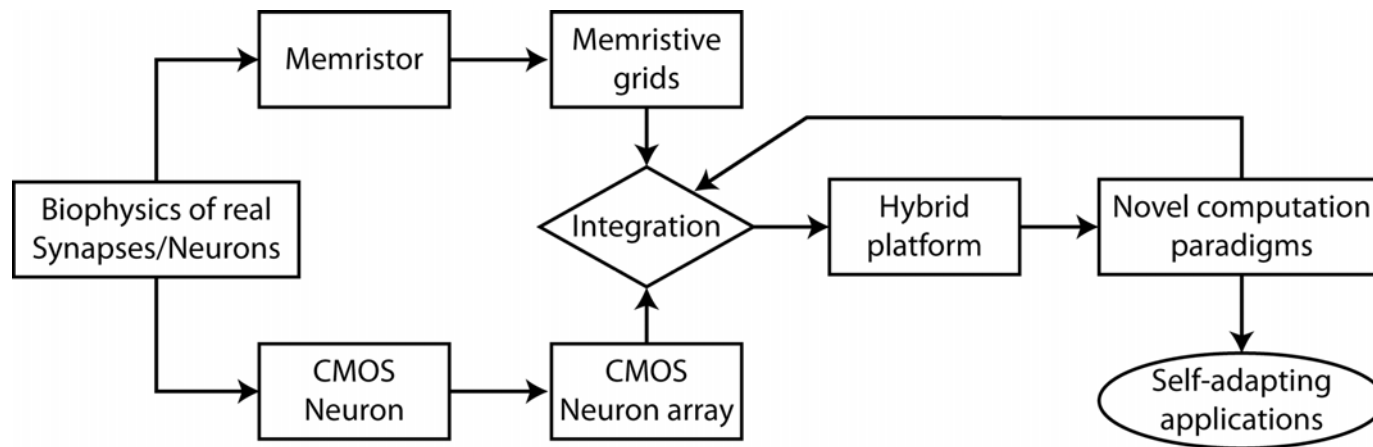
Prof. Robert Plana

Research Objectives

Research interactions

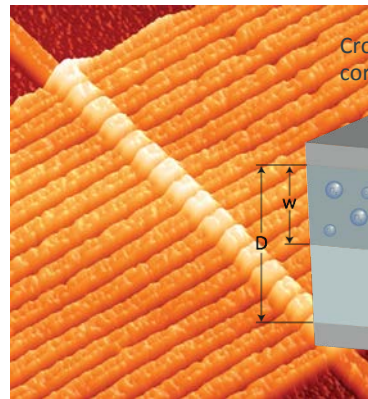
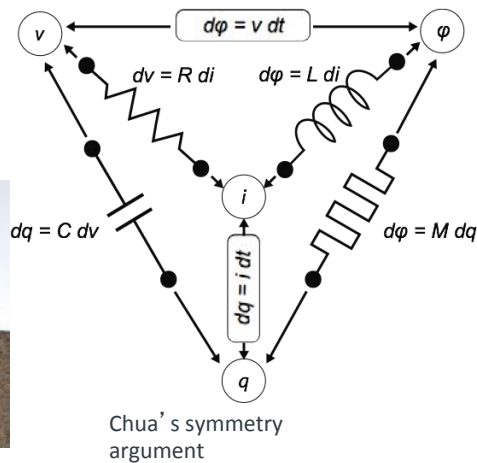


1. Development of biophysically mimetic synapses and neurons
2. Modelling and implementation of neural circuits
3. Development and establishment of novel brain-inspired computational principles
4. Optimisation of device and computational models
5. Practical system-level application of novel computational algorithms
6. Set-up of real-time experiments and benchmarks
7. **Development of system-level hybrid CMOS/Memristor platform to demonstrate autonomous behaviour**

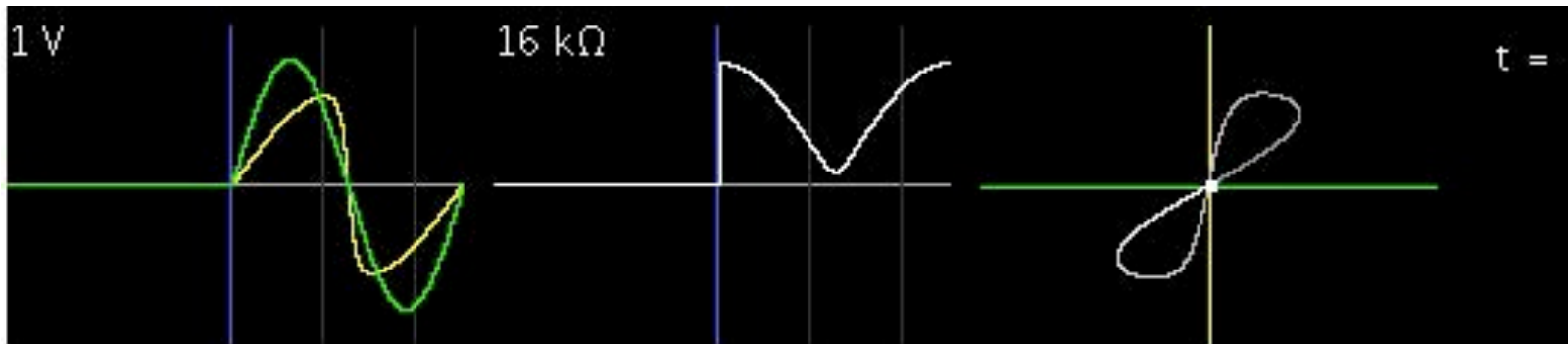
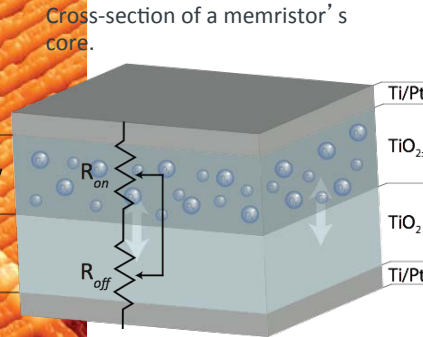


Memristor (memory-resistor)

a “beyond Moore” era



STM image of HP's memristor cross-bar

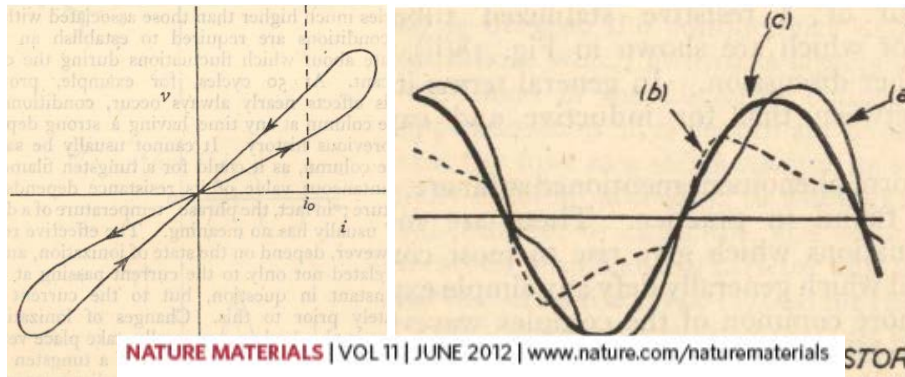


L. Chua, “Memristor-the missing circuit element,” IEEE Trans. Circuit Theory, vol. 18, 1971.

R. Williams, “How we found the missing memristor,” IEEE spectrum, vol. 45, 2008.

Memristors in History

The oldest possible memristor!



commentary

Two centuries of memristors

Themistoklis Prodromakis, Christofer Tournazou and Leon Chua

Memristors are dynamic electronic devices whose nanoscale realization has led to considerable research interest. However, their experimental history goes back two centuries.

Memristors are nonlinear dynamic electronic devices with widespread applications in computer data storage and neuromorphic implementations. The realization of a nanoscale memristor by Hewlett Packard in 2008¹ came almost 40 years after its theoretical inception², and ever since it has precipitated an enormous interest on emerging applications that leverage on the dynamic nature of such devices. Nonetheless, as the research community

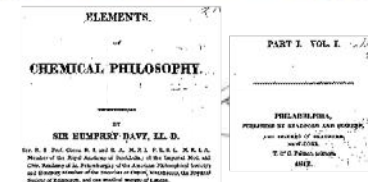
with their main fingerprint being a pinched-hysteresis loop when subjected to a bipolar periodic signal. This particular signature has been explicitly observed in a number of devices for more than one century, while it can be extrapolated for devices that appeared as early as the dawn of the nineteenth century.

Hysteresis is typically noticed in systems and devices that possess certain inertia, causing the value of a physical property to lag behind changes in the mechanism

associated with the displacement of mobile ions or oxygen vacancies^{3,4}, the formation and rupture of conductive filaments⁵ or even the phase transitions⁶ of an active core. And despite the fact that these mechanisms have a more substantial effect in lamella devices, similar attributes can also be supported by considerably larger ionic systems, contingent on the extent of the stimulating cause, the nature of the pertinent ions and the barrier medium that governs their kinetics.



The Oldest Known Memristor Device (1801)



T. Prodromakis and L.O. Chua, "Two Centuries of Memristors", Nature Materials, vol. 11, no 6, Jun 2012.
 Davy, S.H. Elements of Chemical Philosophy. (Philadelphia – Bradford and Inskeep: 1812). 3.
 Francis, V.J., Fundamentals of discharge tube circuits. (Methuen & Co. Ltd: 1948).

Why should we care?

Achieving “more for less”

A disruptive technology with great potential:

- scalable → extension to Moore's law
- highly non-linear characteristic → fast write speeds/computation
- memory effect → bi-stable switch/true analog memory
- locality (memory & computation) → analogue/biomimetic computing
- dynamic response → ideal for adaptive designs
- ultra-low writing potentials → low-power

Analogue and digital circuits are revisited...

memory

logic

dynamic loads

chaotic oscillators

...while novel bio-mimetic designs are facilitated.

synapse emulator

adaptive systems

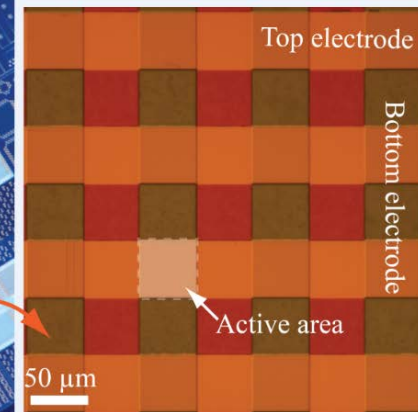
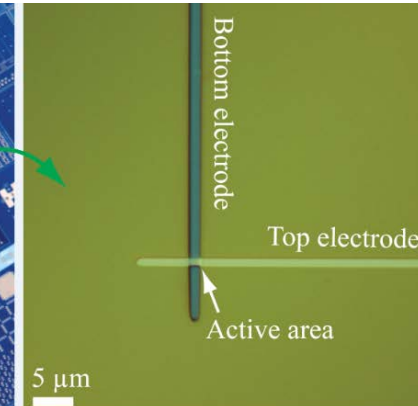
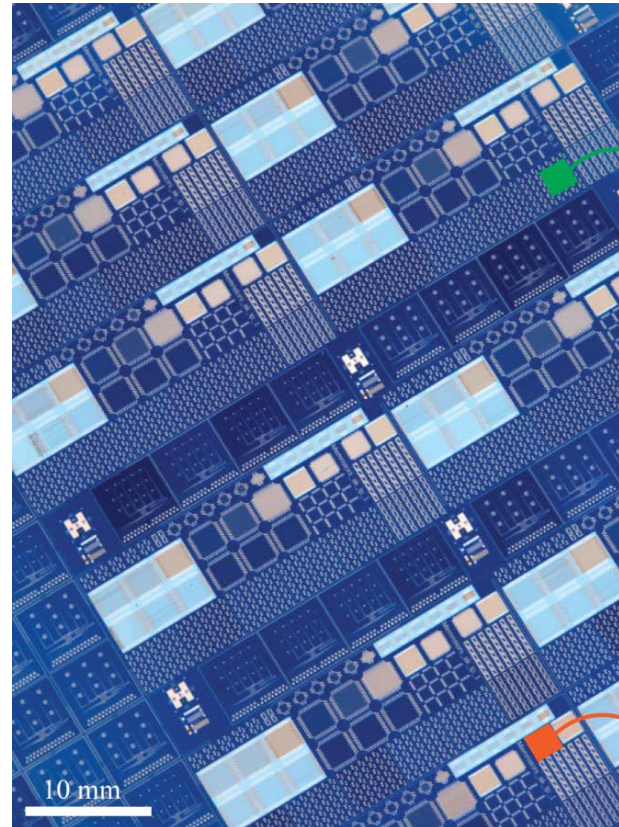
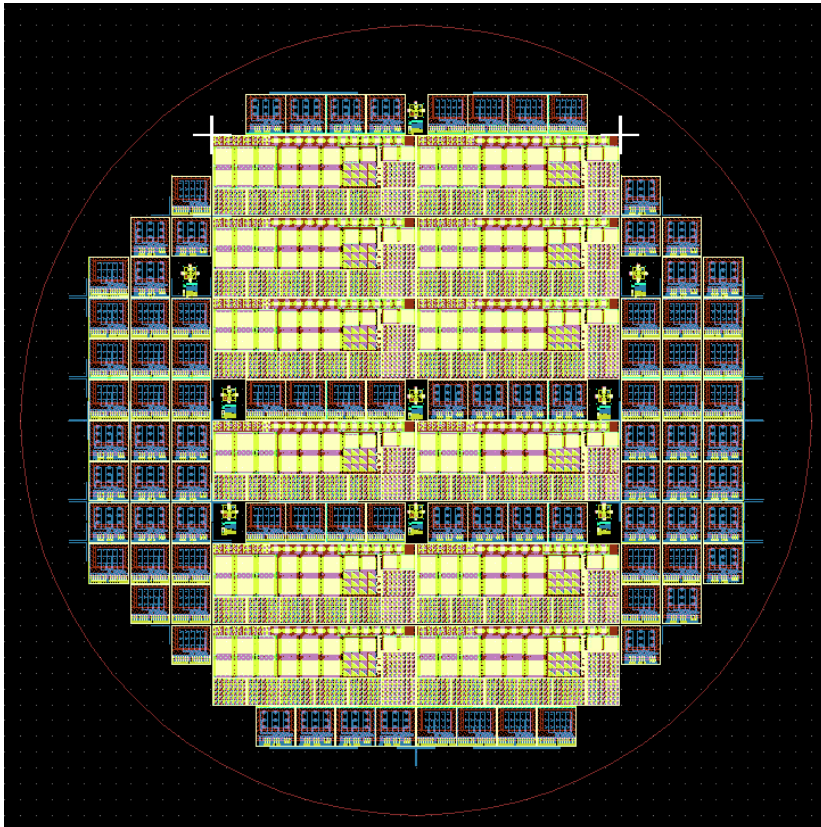
associative memory

neuromorphic processing

Imperial College London

Fabrication recipes: 4" design for conventional Lithography

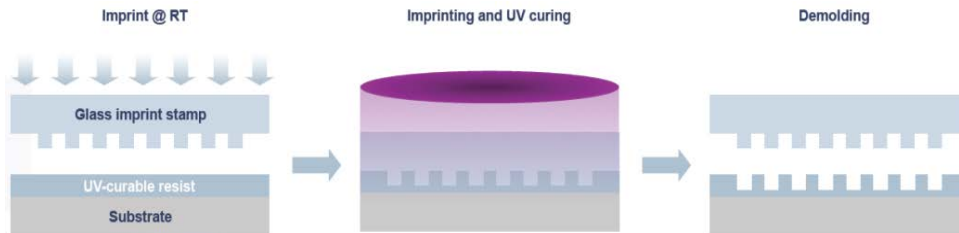
Stand-alone devices



Cross-bar devices

- Devices: 1×1 , 2×2 , 5×5 , 10×10 , 50×50 and $100 \times 100 \mu\text{m}^2$
- TiO_x , HfO_x , Ta_xO_y and ITO active layers + Phase change (GLS) and Ferroelectrics

Nano-Imprint Lithography

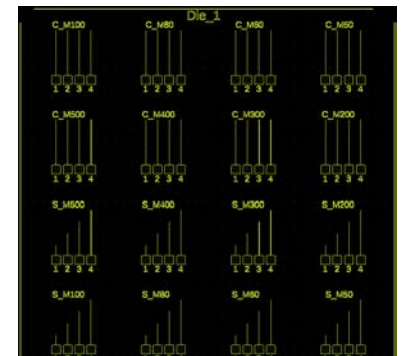
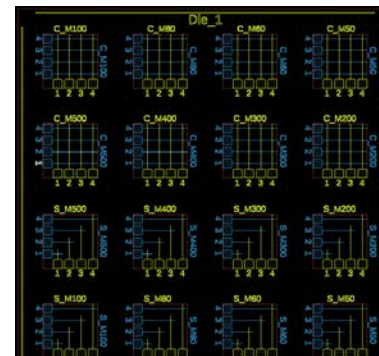
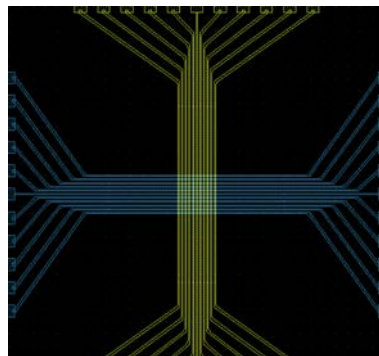
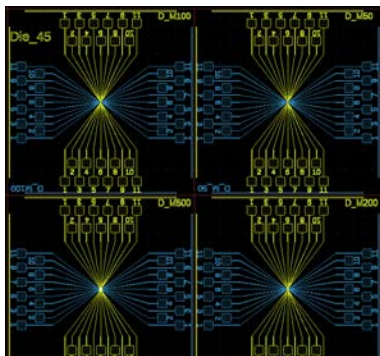
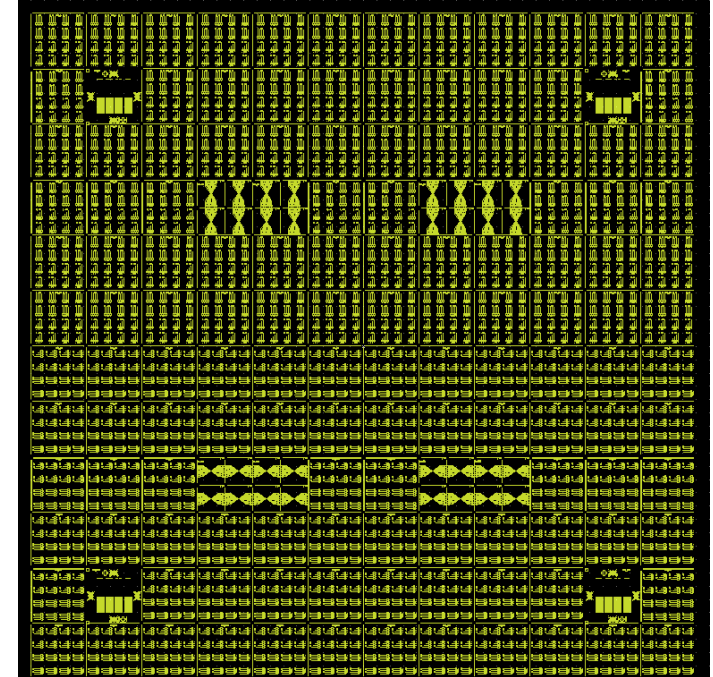


1 Mask only for both TE & BE
Sent for fabrication on 30/05/2012



Minimum electrode width: 20nm

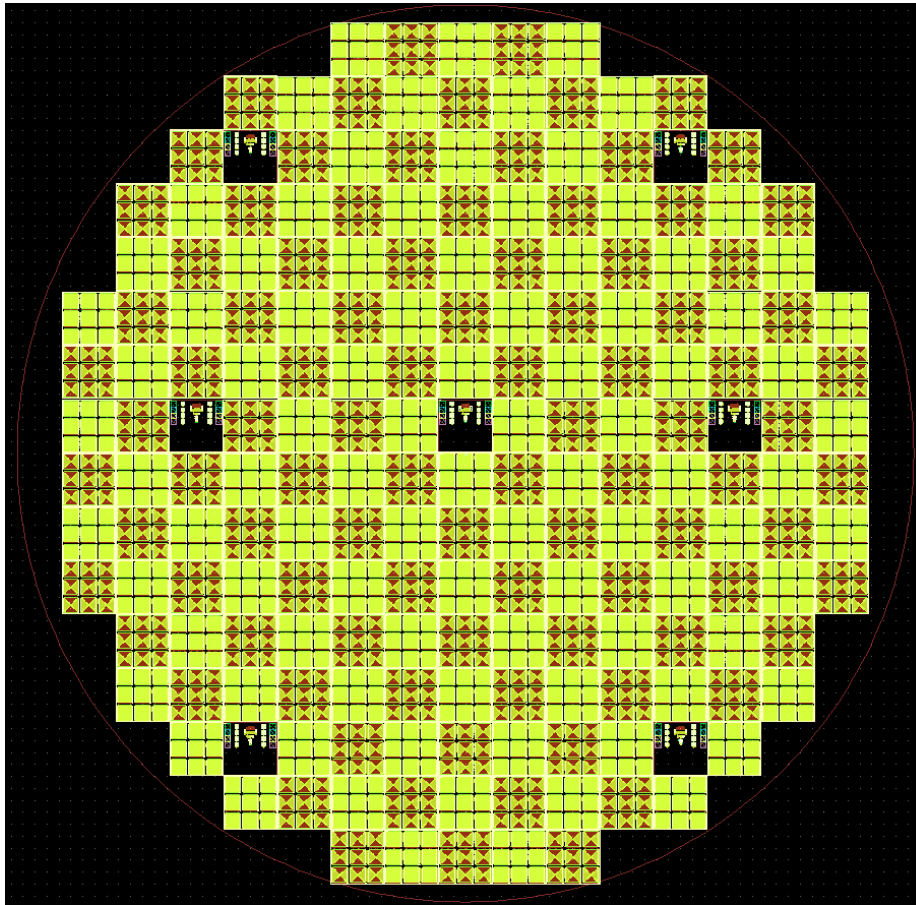
Devices with 50x50, 60x60, 80x80, 100x100, 200x200, 300x300, 400x400 & 500x500 nm²



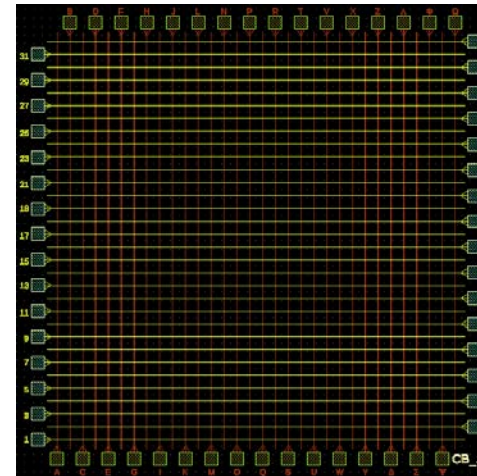
University of Southampton

Southampton Nanofabrication Centre (SNC)

Conventional Lithography @ SNC

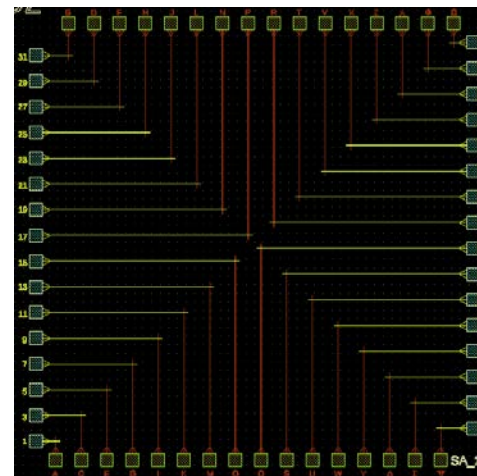


Devices: 1x1, 2x2, 5x5, 10x10, 30x30, 40x40, 50x50 and 60x60 μm^2



- Improved version with comb-like crossbar configuration
- 1 Kbit/chip

Cross-bar devices



Stand-alone devices

First 6" prototype fabricated at SNC

Happy Boss 😊



E-Beam Lithography

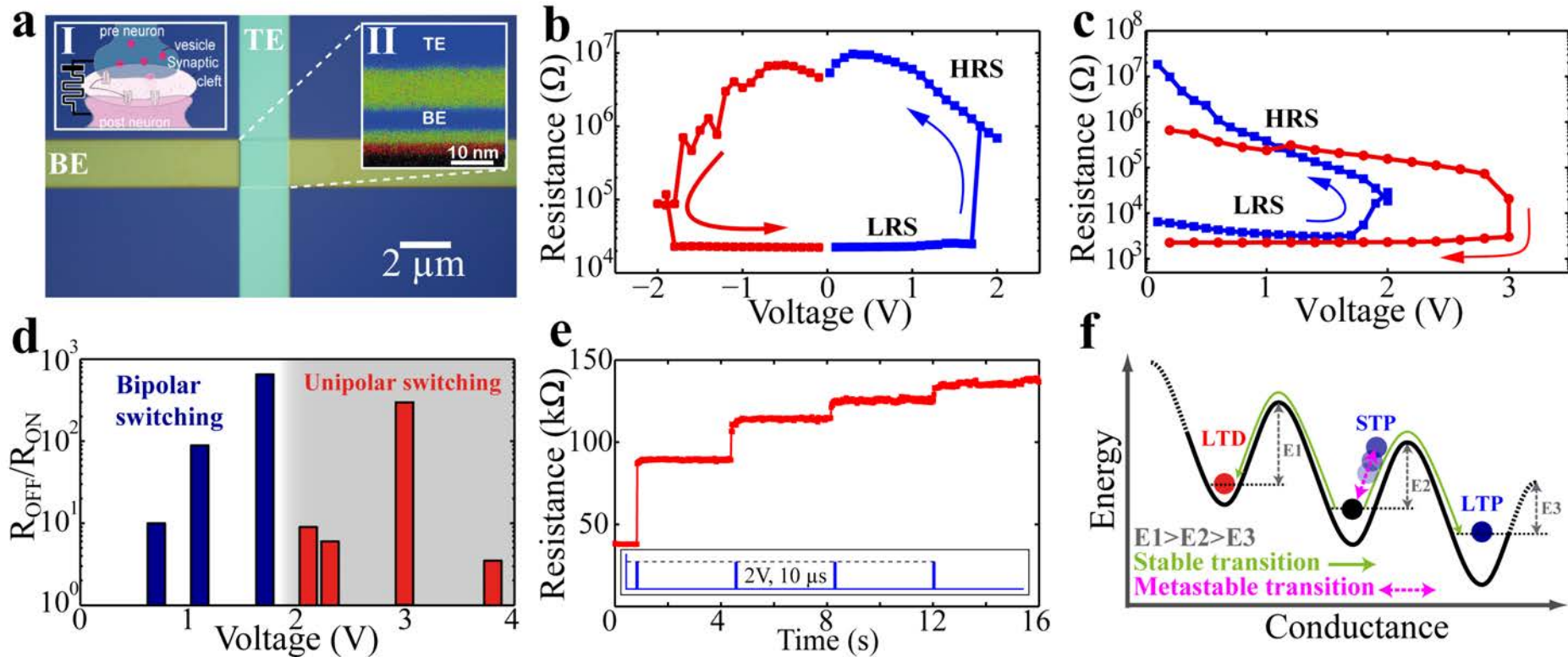
- + Nanometre scaled devices (sub 10 nm)
- Slow
- Expensive

Nano-Imprint Lithography

- + Nanometre scaled devices (sub 50 nm)
- + Low cost
- + Mass production
- NIL Masters are expensive. However, we fabricate them at SNC and we can replicate them using flexible masters.

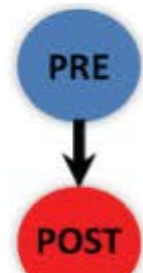
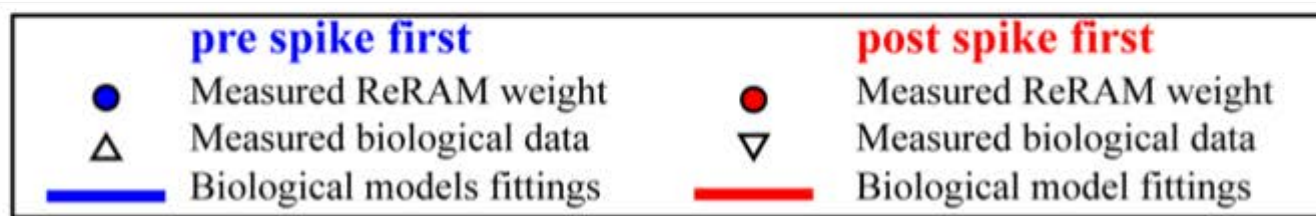
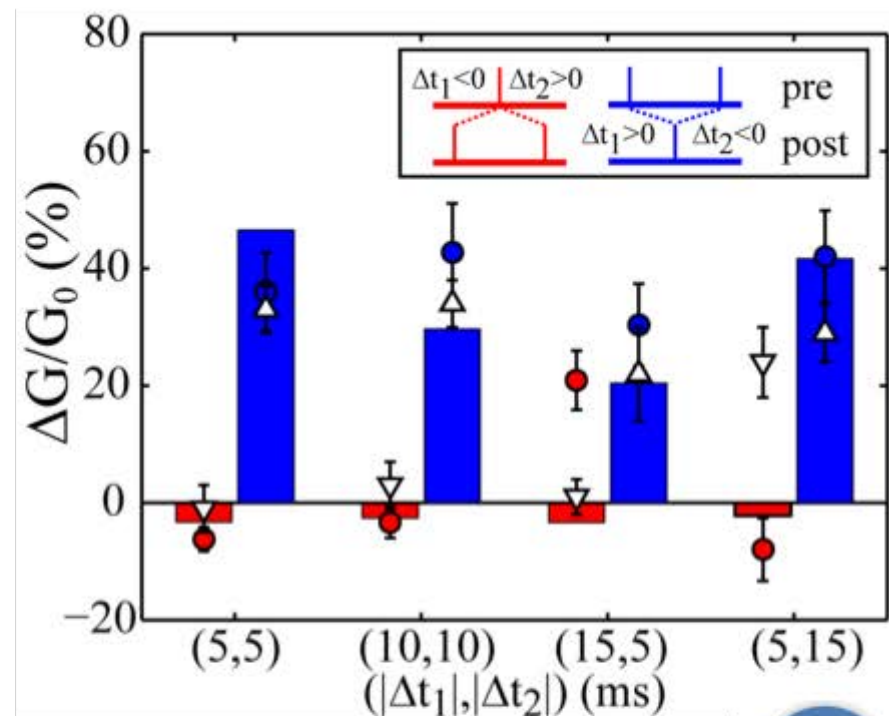
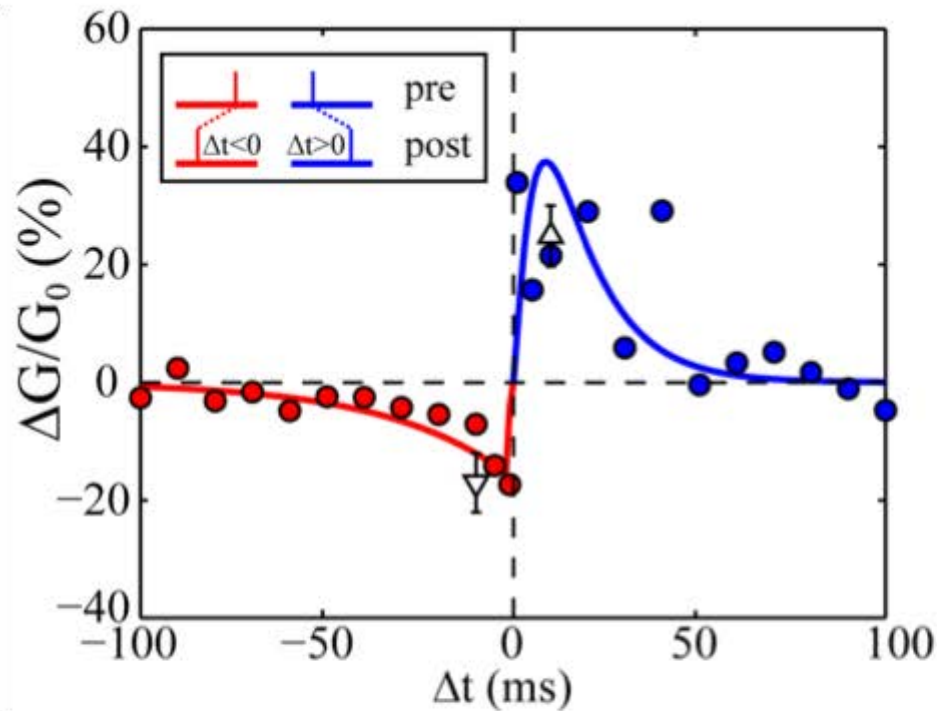
Memristive Synapses

TiO₂ memristors can support both bipolar and unipolar, volatile and non-volatile switching



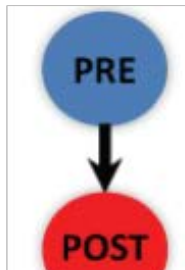
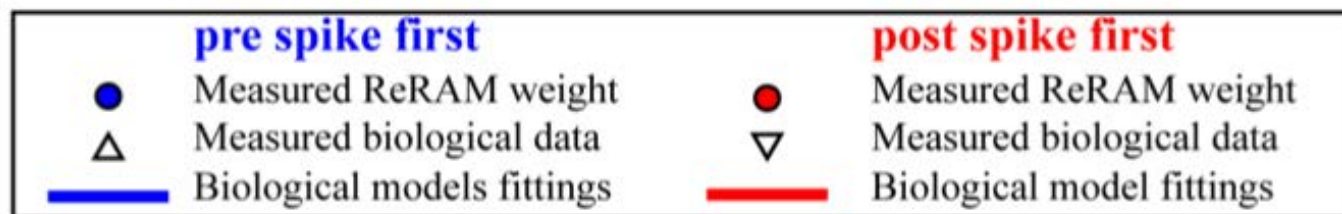
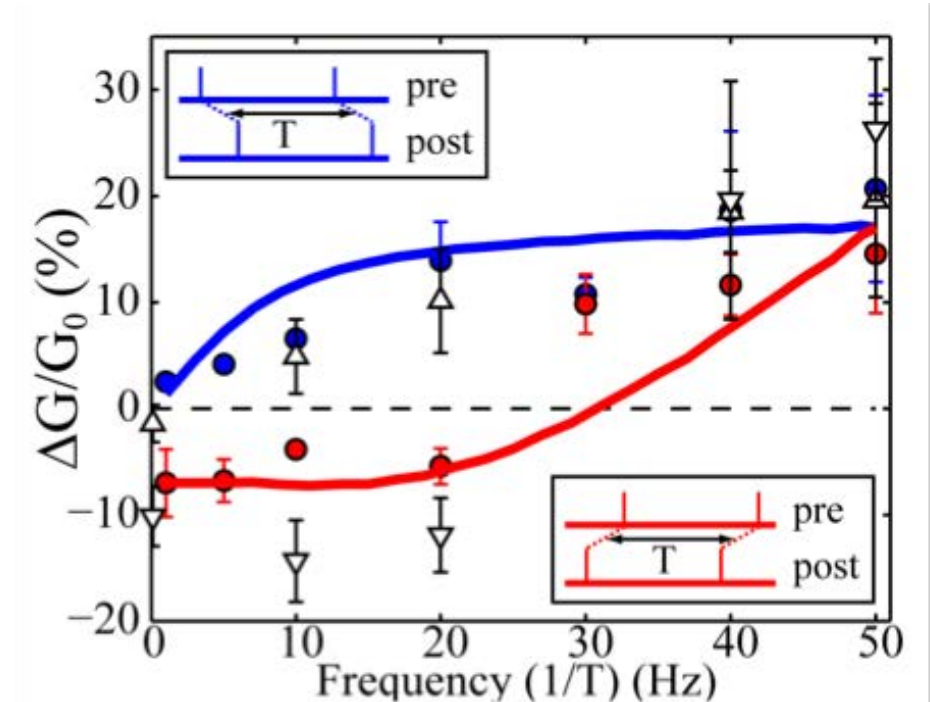
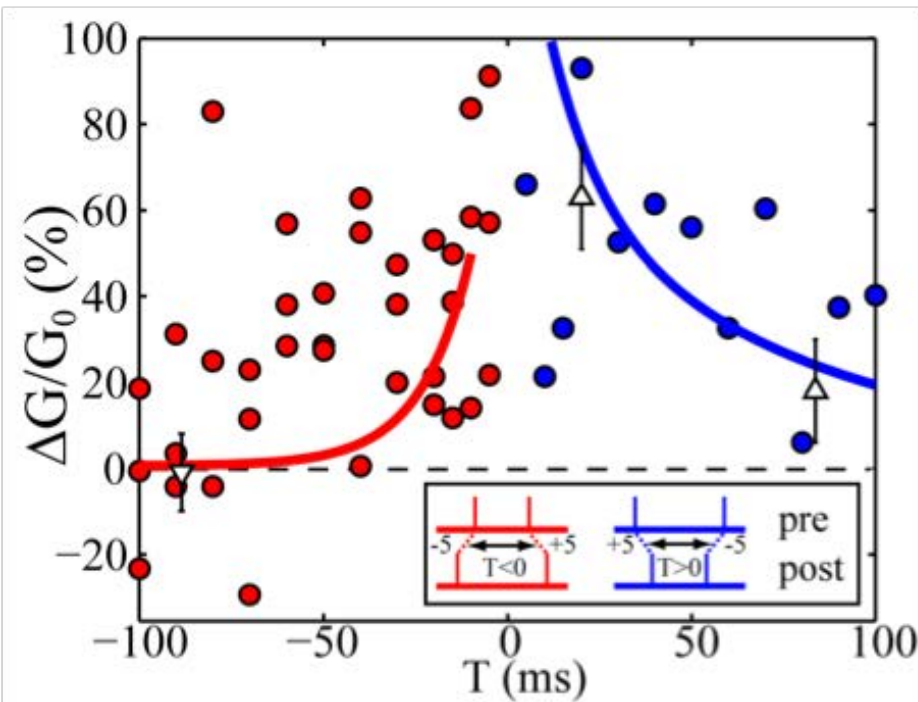
Memristive Synapses

Memristive synapses support long-term pair-based plasticity rules



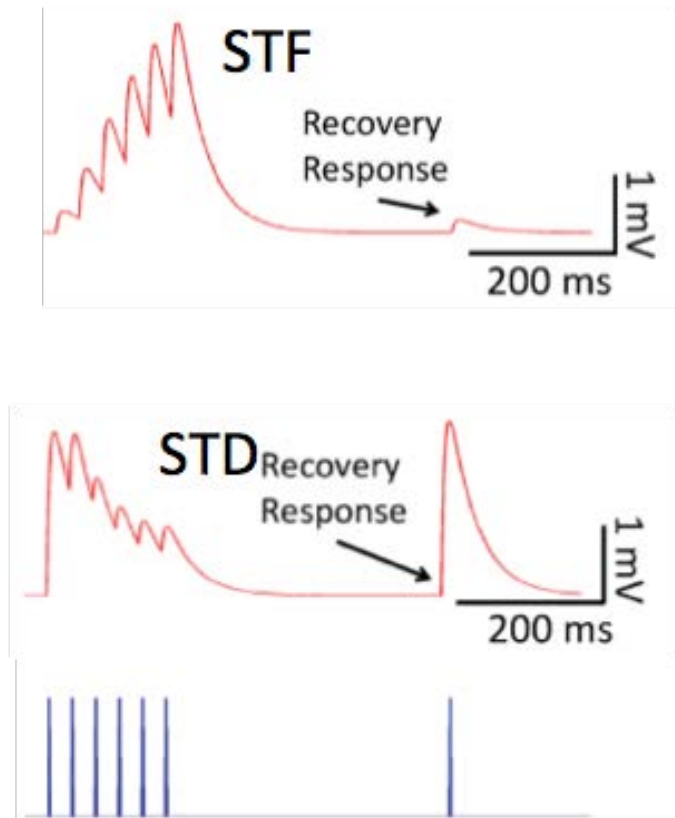
Memristive Synapses

Memristive synapses support long-term pair-based plasticity rules

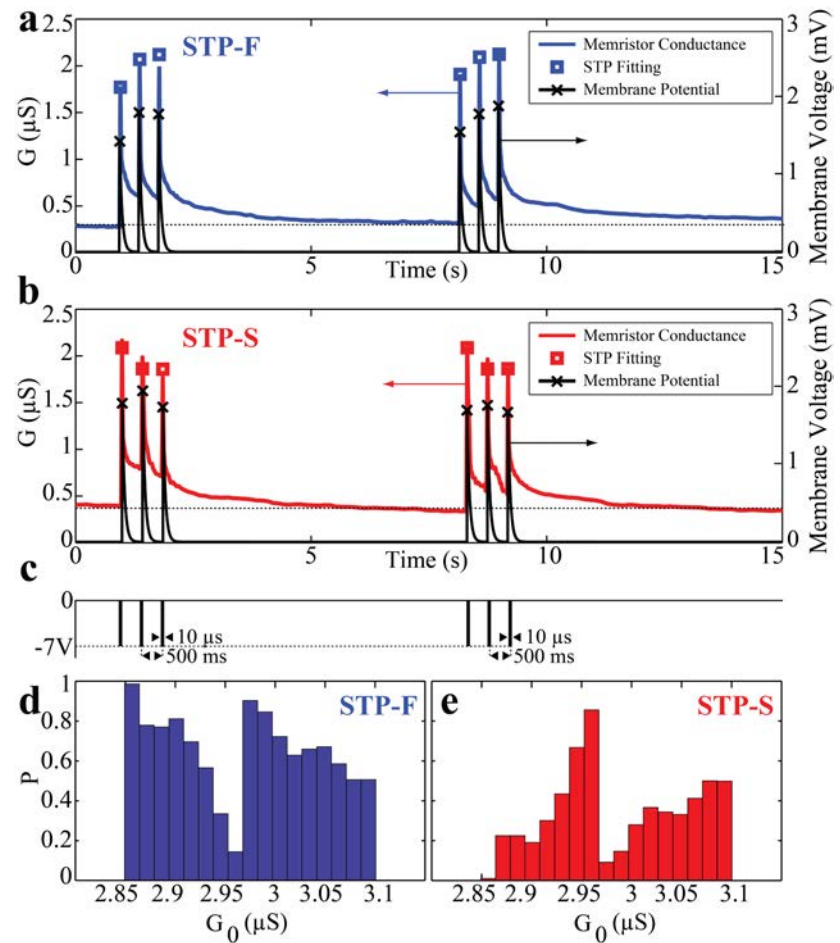


Memristive Synapses

A single memristor functioning both as a facilitating and depressing synapse

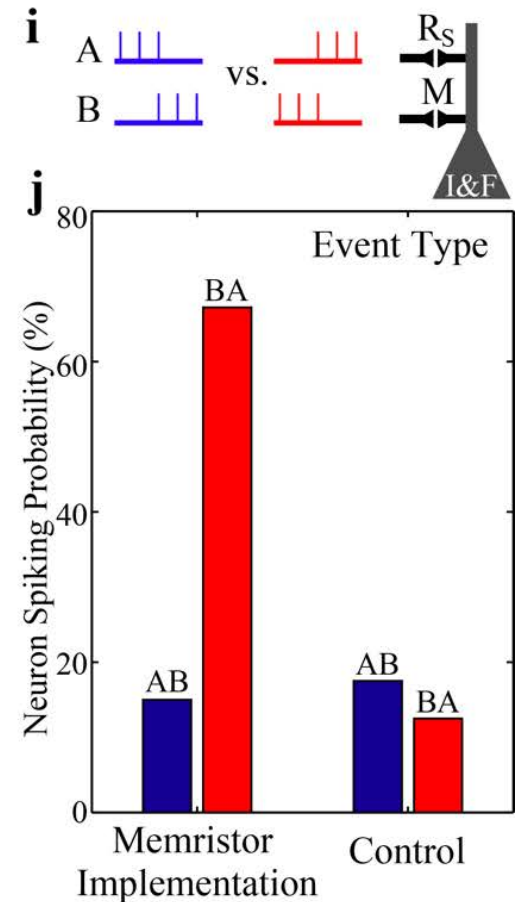
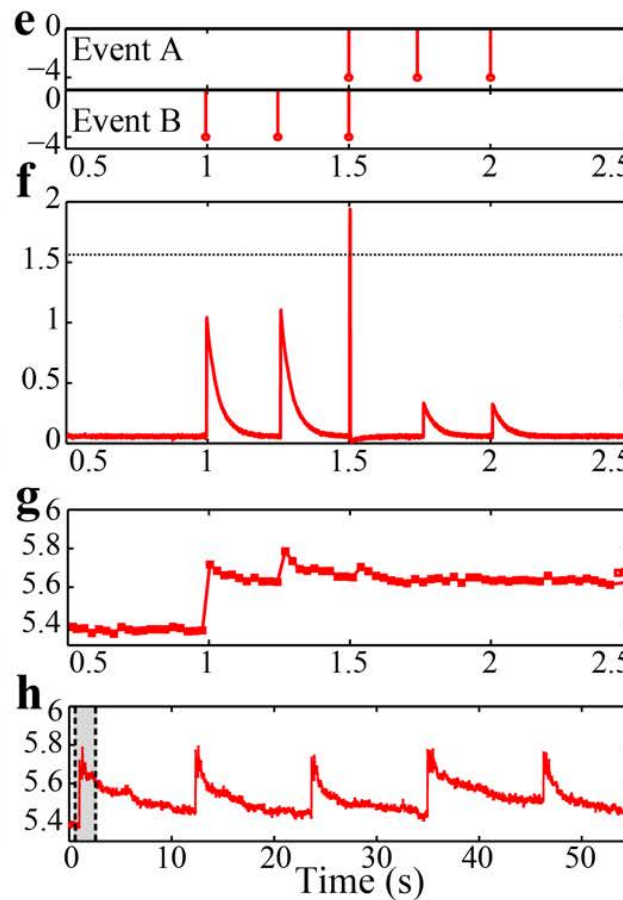
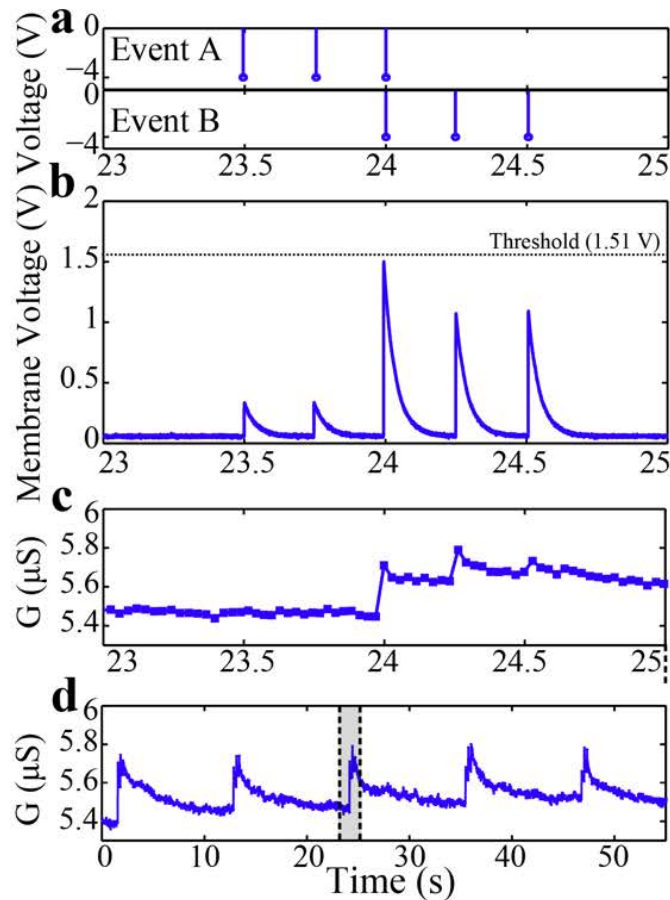


“Weak synapses tend to be facilitating while strong synapses tend to be depressing”



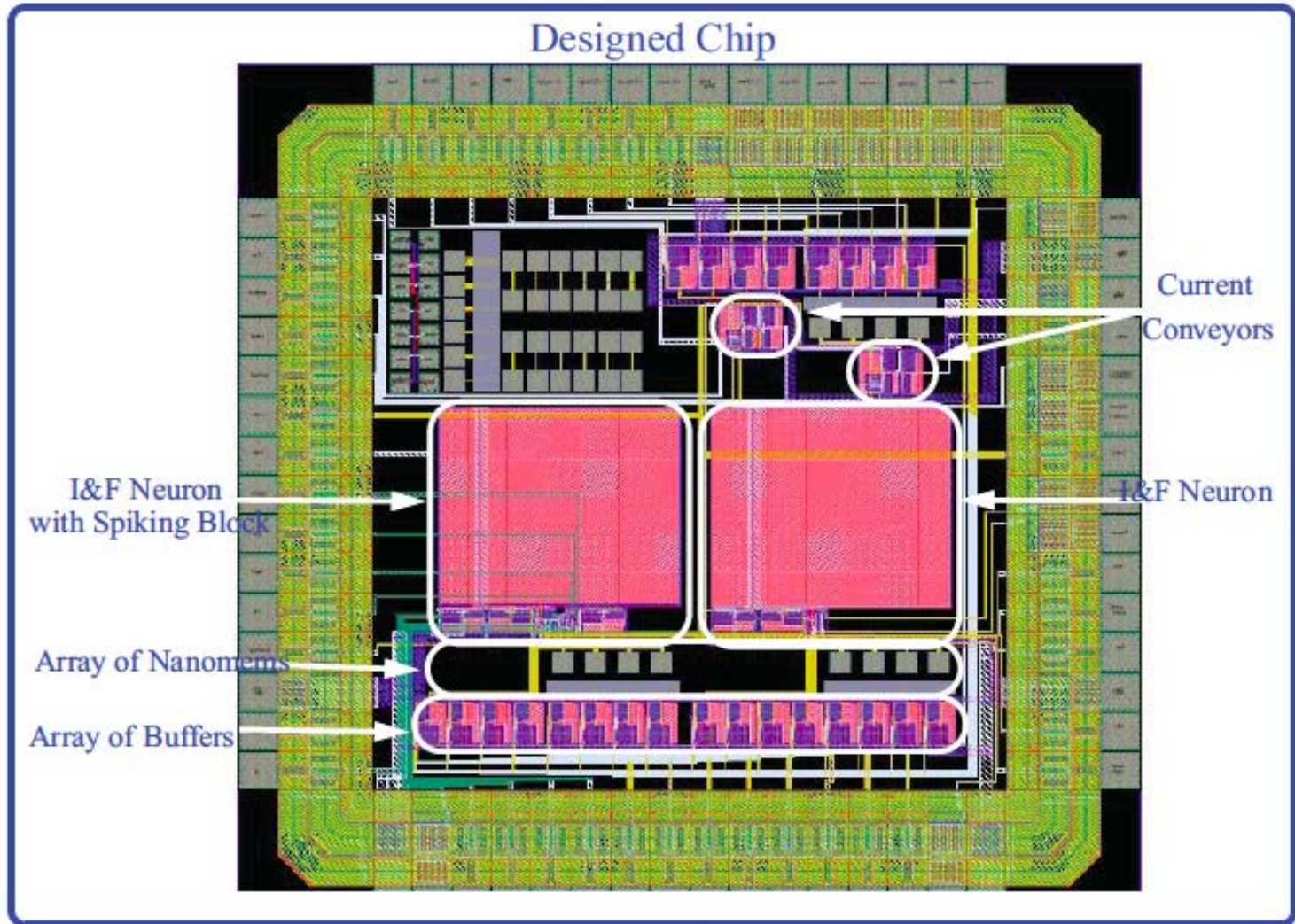
Memristive Synapses

Application of memristor short-term dynamics in detecting concurrency of events



CMOS integration

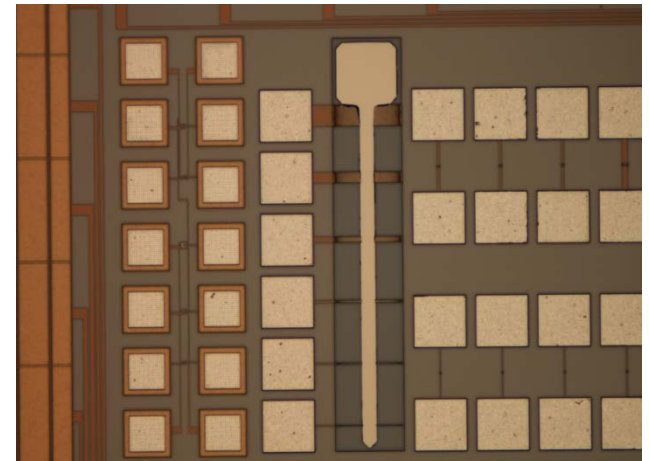
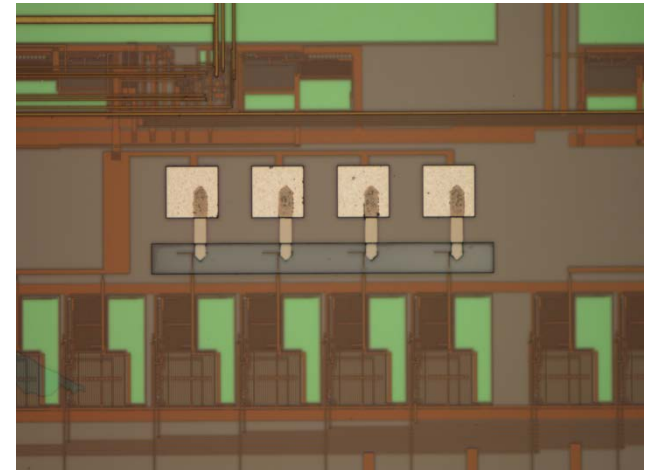
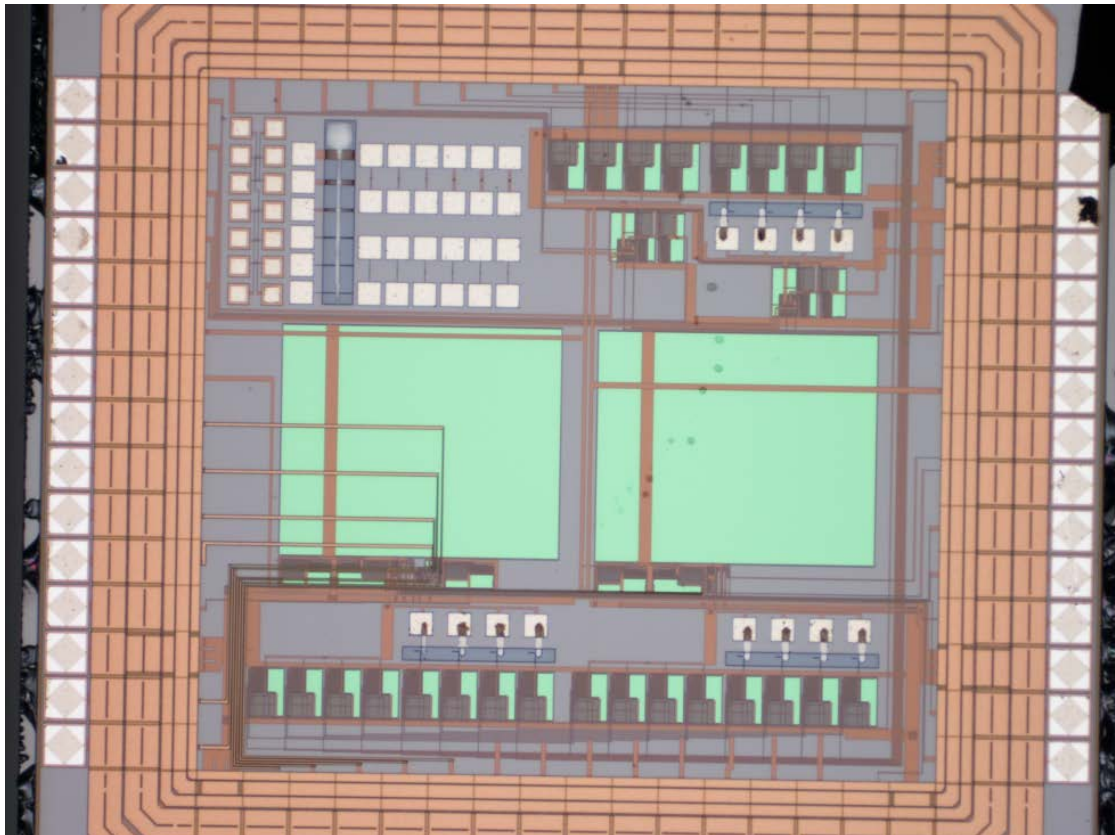
Gen 2 (IMSE)



CMOS integration

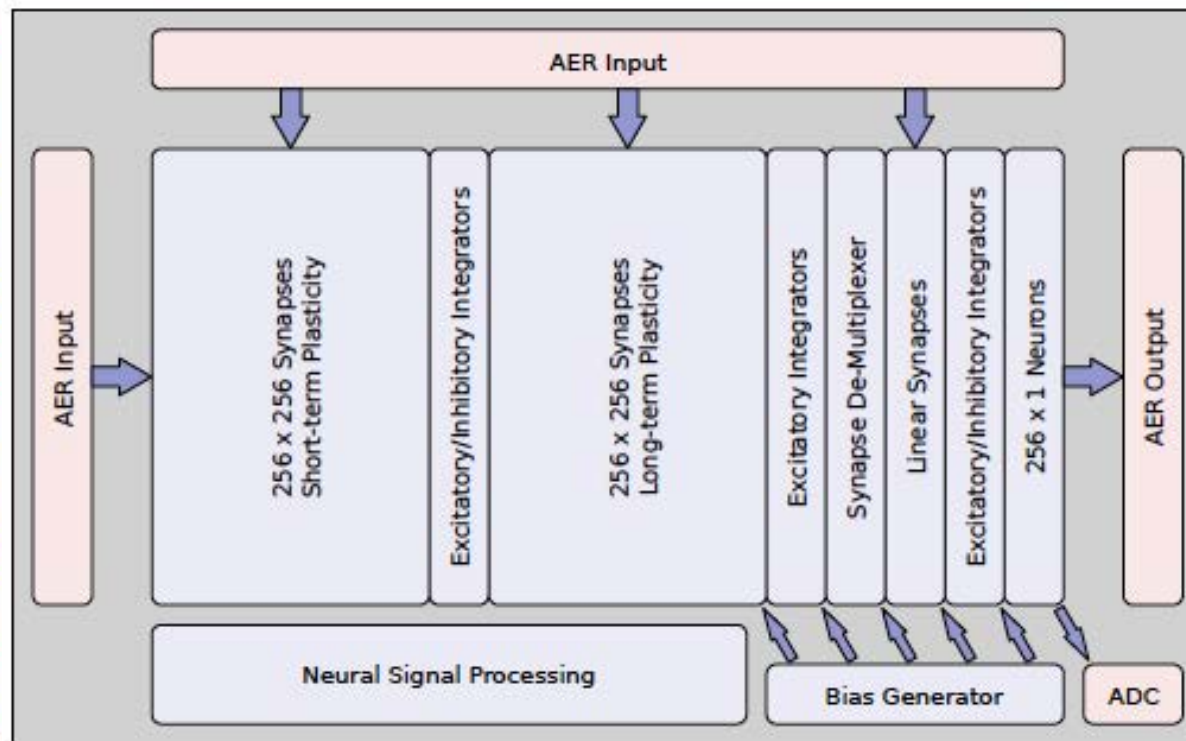
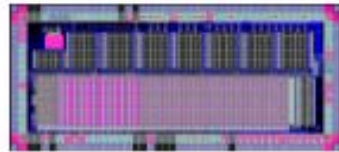
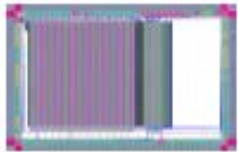
Gen 2 (IMSE)

- Active Layer and TE masks were fabricated to obtain Extrinsic devices



CMOS integration

Gen 3 (INI)



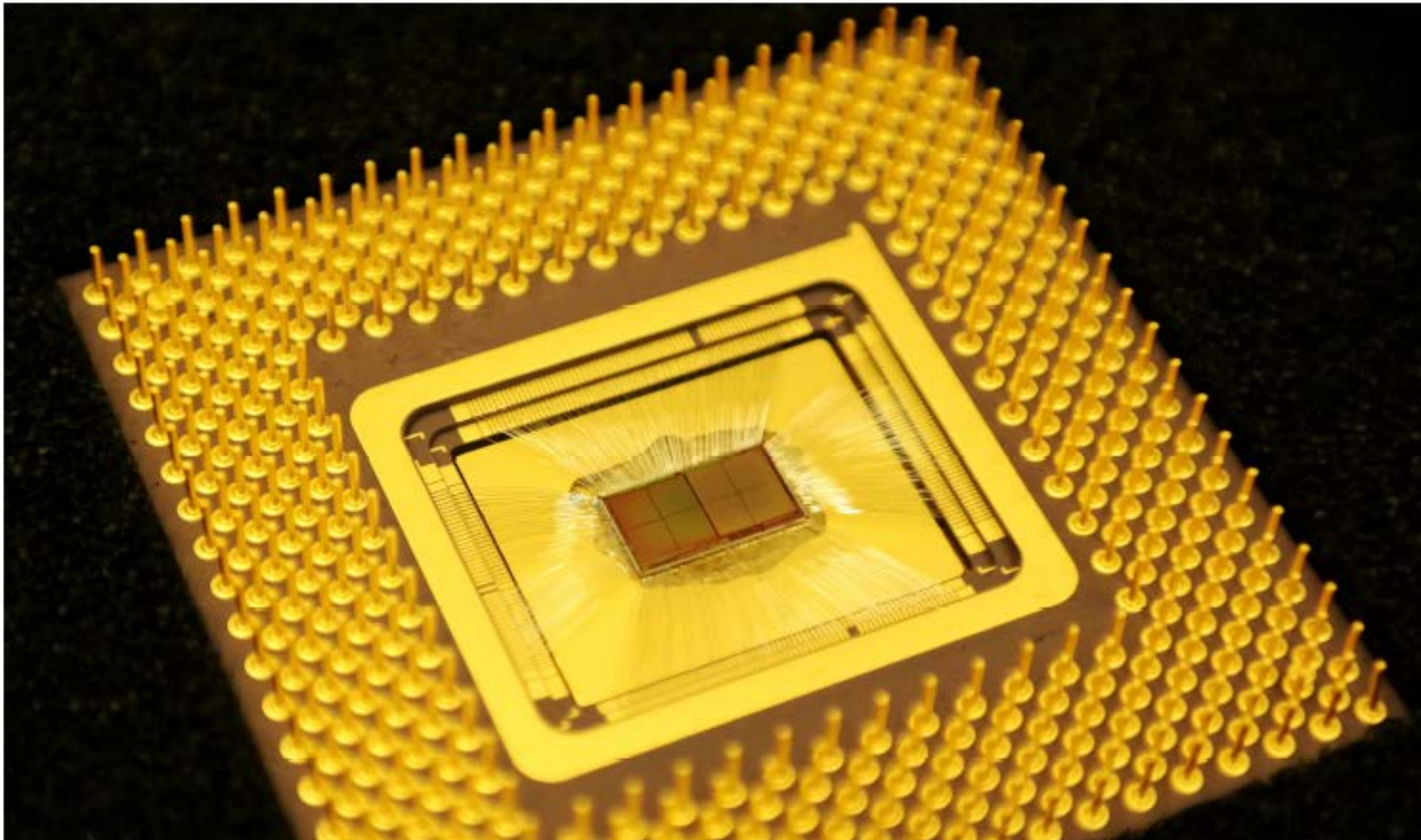
- 256 neurons
- 256 linear synapses
- $2 \times 64K$ synapses (short-term, long-term)
- homeostatic plasticity
- configurable recurrent connectivity

Technology: AMS $0.18 \mu m$ 6M CMOS

Size: 9.4 mm $\times$ 5.5 mm

The latest multi-neuron chip

128K plastic synapses and 256 neurons



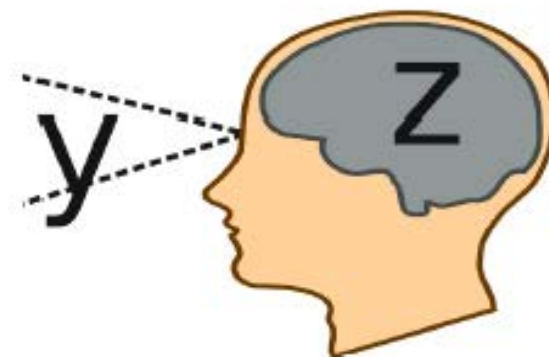
Probabilistic inference with spiking networks

“The Bayesian brain”:

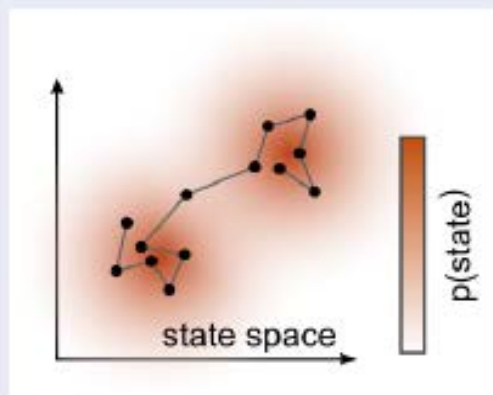
$$p(\mathbf{z} | \mathbf{y}) \propto p(\mathbf{z}) \cdot p(\mathbf{y} | \mathbf{z})$$

$\mathbf{y}$: Observations

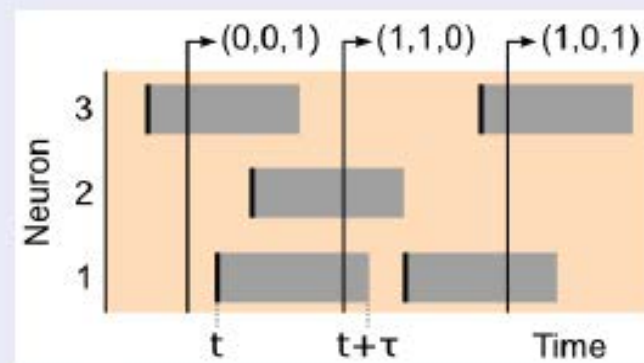
$\mathbf{z}$: Hidden causes



The Sampling-Hypothesis



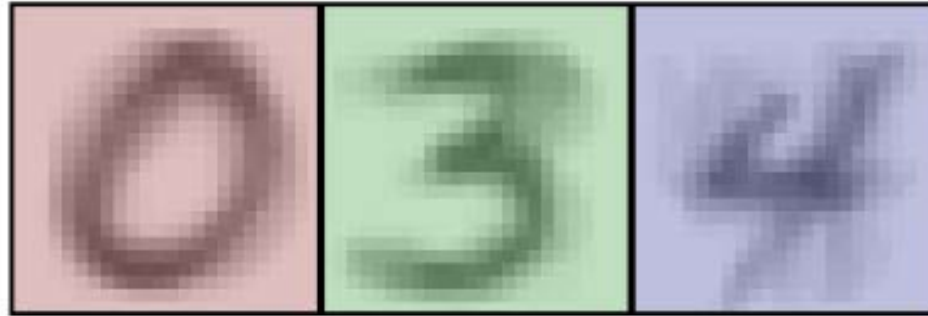
(Fiser et al, 2010)
(Haefner et al, Sat.)



(Buesing et al, 2011)

Motivation: Identifying categories

Abstract
categories z
(latent variables) $\rightarrow$



Observed data $y \searrow$



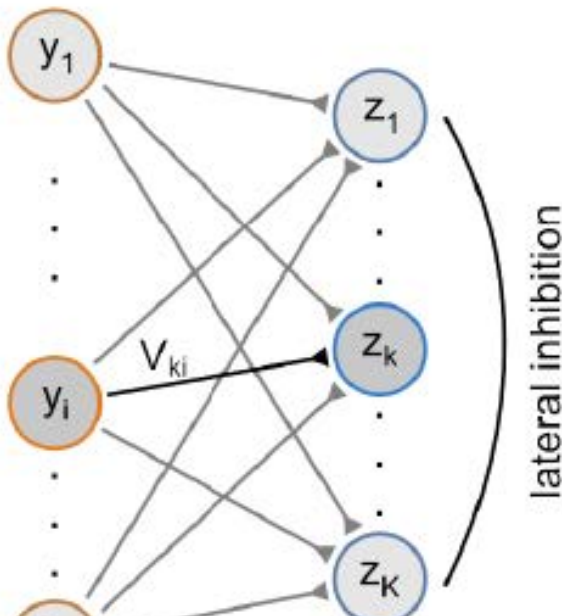
Winner-take-all network

Network architecture

- ▶ Spiking inputs y_i (e.g. external sources)
- ▶ Spiking output neurons z_k (stochastic)
- ▶ Strong lateral, pair-wise inhibition
- ▶ Plastic excitatory synapses V_{ki} (memristors)

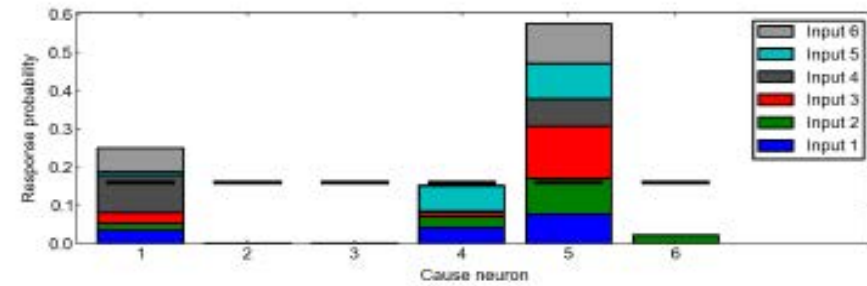
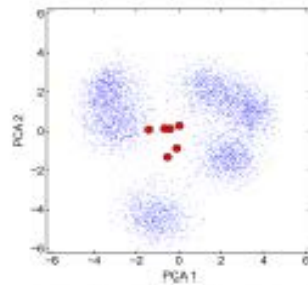
Stochastic neuron model

- ▶ Membrane potential
$$u_k = b_k + \sum_i V_{ki} y_i + \text{lateral inh.}$$
- ▶ Synaptic time constant τ (e.g. 10ms)
- ▶ Intrinsic excitability b_k of output neurons
- ▶ Instantaneous firing rate: $\rho_k = \frac{1}{\tau} \exp(u_k)$

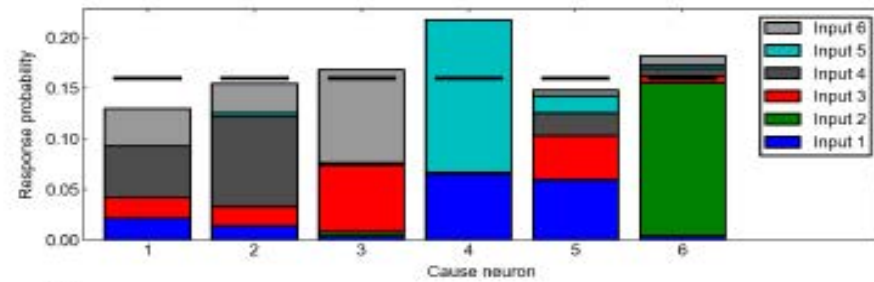
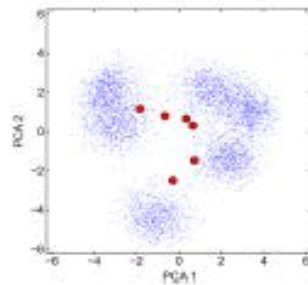


Synthetic data set

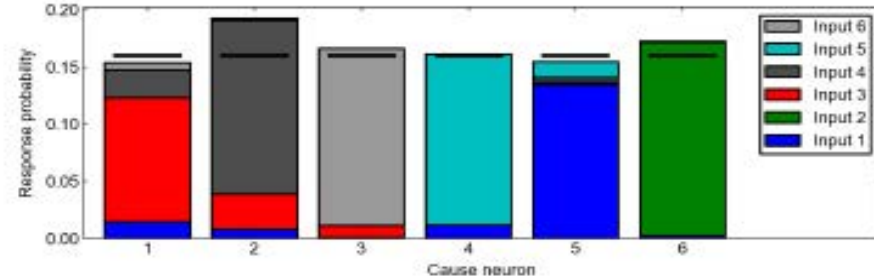
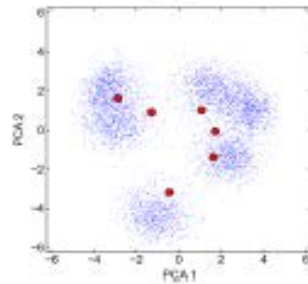
T=0



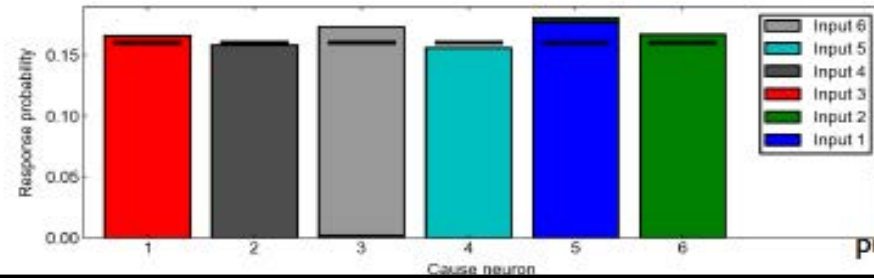
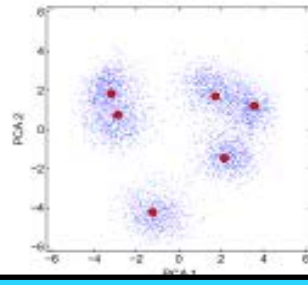
T=4k



T=8k

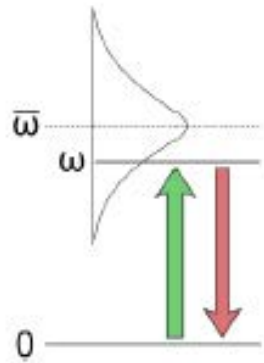


T=30k

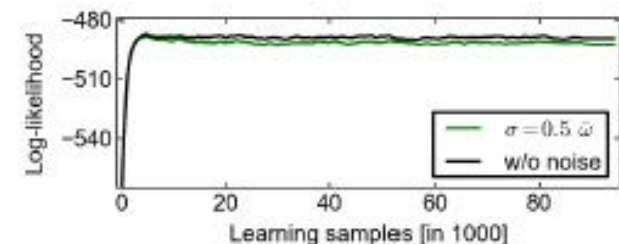
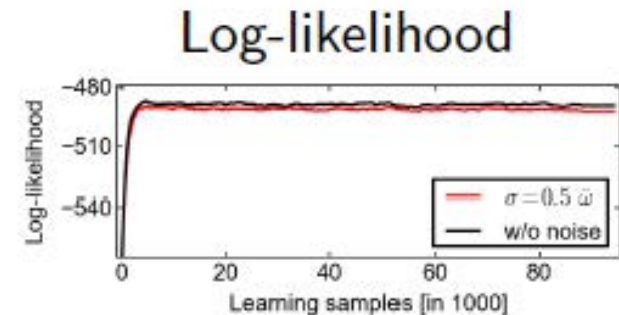
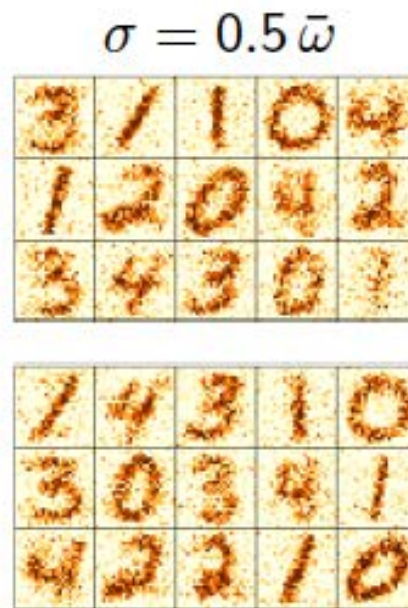
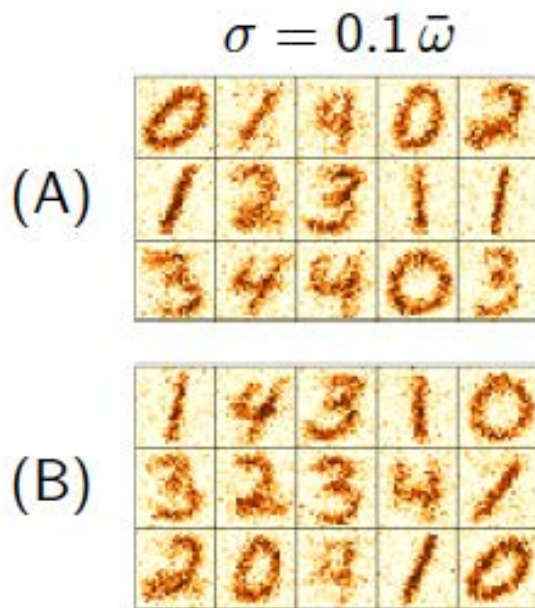


pneuma 2014

Robustness to memristor variability



- Apply noise to binary synaptic weight ω
- From normal distribution $\omega \sim \mathcal{N}(\bar{\omega}, \sigma^2)$
- Two scenarios:
 - (A) Static: Memristor property
 - (B) Dynamic: $0 \xrightarrow{\text{LTP}} \omega \sim \mathcal{N}(\bar{\omega}, \sigma^2)$



PNEUMA structure



institute of
neuroinformatics



University of
Zurich ^{UZH}



WP1 Development of memristive grids

- D1.1 (9m) Fabrication of single memristor cells
- D1.2 (12m) Memristor model with detailed specifications (R_{ON}/R_{OFF} , V_T)
- D1.3 (24m) Fabrication of 2-D memristive grids
- D1.4 (36m) Process flowchart and preliminary monolithic specimens

DONE

WP2 Development of CMOS Support

- D2.1 (6m) Neuron specifications
- D2.2 (12m) Neuron design sent for fabrication
- D2.3 (24m) Neuron array sent for fabrication
- D2.4 (36m) Test of hybrid CMOS-memristive system

DONE

WP3 Biophysically realistic hybrid CMOS/memristive synapses

- D3.1 (6m) Specifications for synaptic CMOS and memristive circuits
- D3.2 (12m) Hybrid CMOS/memristive neuromorphic synapse circuits
- D3.3 (24m) Hybrid CMOS/memristive spike-based learning device
- D3.4 (36m) Spike-based learning system characteristics and demo

DONE

WP4 Development of novel computational paradigms

- D4.1 (24m) Report on novel brain-inspired paradigms for computation and self-organization in neural **DONE.**
- D4.2 (36m) Report on possible applications of self-adapting circuits.

WP5 Development of integration technologies

- D5.1 (6m) Interfacing of prototypes/Fabrication of NIL masks
- D5.2 (16m) First integrated CMOS/memristor platforms (single-elements)
- D5.3 (30m) Integrated CMOS/Memristor platforms (networks)
- D5.4 (36m) Monolithic integration approach

DONE

PNEUMA organisation



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Dr Themis Prodromakis

Imperial College London
Centre for Bio-Inspired
Technology
London, SW7 2AZ, UK
+44 (0)20 7594 0840
t.prodromakis@imperial.ac.uk

Plasticity in NEURAL Memristive Architectures

Beyond Autonomic systems - the Challenge of Consciousness

During the past two decades, philosophers, psychologists, cognitive scientists, clinicians and neuroscientists strived to provide authoritative definitions of consciousness within a neurobiological framework. Engineers have more recently joined this quest by developing neuromorphic VLSI circuits for emulating biological functions. Yet, to date artificial systems have not been able to faithfully recreate natural attributes such as true processing locality (memory and computation) and complexity (10^{10} synapses per cm^2), preventing the achievement of a long-term goal: the creation of autonomous cognitive systems.

This project aspires to develop experimental platforms capable of perceiving, learning and adapting to stimuli by leveraging on the latest developments of five leading European institutions in neuroscience, nanotechnology, modeling and circuit design. The non-linear dynamics as well as the plasticity of the newly discovered memristor are shown to support Spike-based- and Spike-Timing-Dependent-Plasticity (STDP), making this extremely compact device an excellent candidate for realizing large-scale self-adaptive circuits; a step towards "autonomous cognitive systems". The intrinsic properties of real neurons and synapses as well as their organization in forming neural circuits will be exploited for optimizing CMOS-based neurons, memristive grids and the integration of the two into real time biophysically realistic neuromorphic systems. Finally, the platforms would be tested with conventional as well as abstract methods to evaluate the technology and its autonomous capacity.

ERA-Net CHIST-ERA

CHIST-ERA stands for "European Coordinated Research on Long-term Challenges in Information and Communication Sciences & Technologies ERA-NET".

The focus of CHIST-ERA is long-term transformational research. Its principal objective is to reinforce the transnational collaboration between Member States in challenging multidisciplinary research in the area of ICST, and to integrate the related national research communities in Europe through the funding of transnational research projects.

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Centre for Bio-Inspired
Technology
London, SW7 2AZ, UK
+44 (0)20 7594 0840
t.prodromakis@imperial.ac.uk

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FUTURE & EMERGING TECHNOLOGIES

CAS-FEST 2014

ISCAS2014

INTERNATIONAL SYMPOSIUM ON CIRCUITS AND SYSTEMS
1-5 JUNE 2014 MELBOURNE, AUSTRALIA



Memristive devices, circuits, systems and applications

- Functional materials and devices
- Advanced nanoelectronic technologies
- Advanced characterization
- Information storage at the nano-scale
- Bio-inspired/-mimetic memory and computation
- Memristive Sensory Systems
- Neuromorphic circuits and systems
- Memristor-based circuits
- Theory and modeling
- Applications exploiting memristors
- CMOS integration
- Cellular automata and array computing
- Chaos and complex networks

<http://iscas2014.org>

Reliably unreliable nanotechnologies

A brief description of the fellowship

This fellowship aims exploiting the strong emergence of ultra-thin functional oxides, nanoscale resistive switching elements and large-scale systems of the same. We will first investigate the effect of quantum phase transitions and the mechanisms leading into thermodynamically stable/unstable long-range order/disorder of distinct materials. These mechanisms will then be exploited in nanoscale solid-state devices for establishing the state-of-the-art in non-volatile multi-state memory but also volatile elements that could potentially be employed as dynamic computational elements. The rich-dynamics of the later will be compared against reaction-diffusion mechanisms of naturally occurring nano-systems to facilitate novel design paradigms and emerging ICT applications for substantiating unconventional computation formalisms. A successful outcome will demonstrate a mature memristive device manufacturing technology that will be supported by the necessary design tools, for taking CMOS technology far beyond its current state-of-art.



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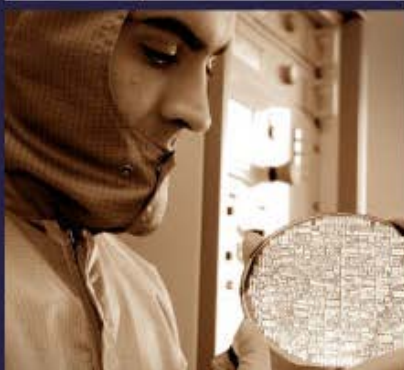
6

11/27/2013 @ 14:00

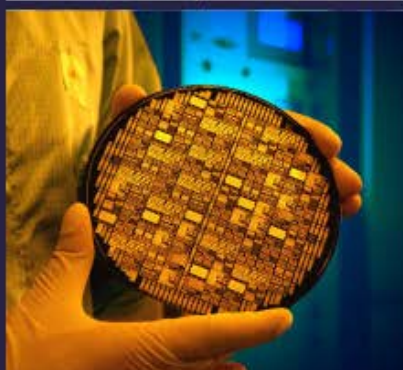


In this talk Dr Prodromakis will present the functional properties of memristors, an emerging nanoscale memory technology. He will also discuss the physical switching mechanisms and how these unreliable mechanisms can be reliably exploited in practical applications, particularly in analogue IC design and neuromorphic systems.

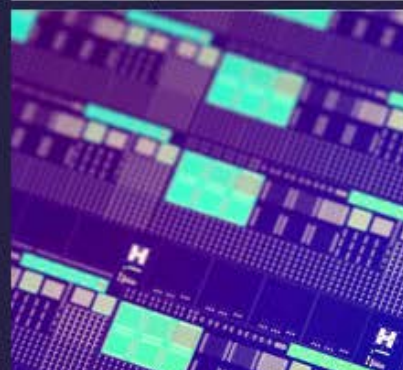
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FUNCTIONAL OXIDES



NANO DEVICES

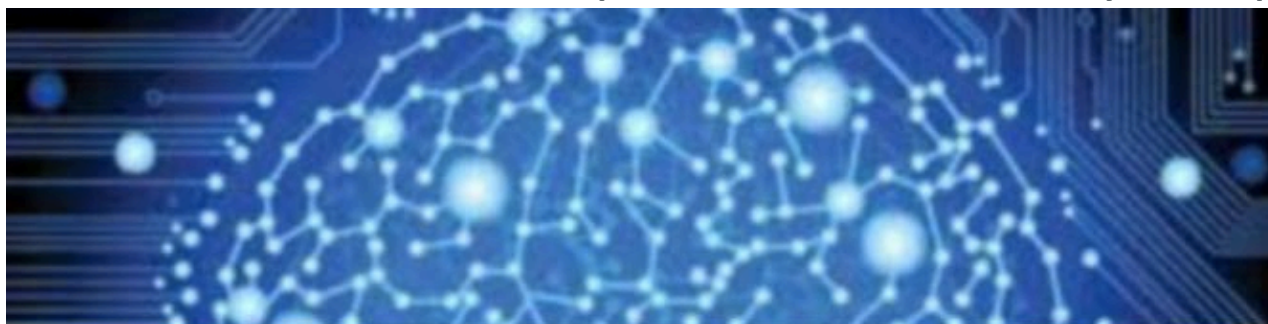


ADAPTIVE CIRCUITS



Future Directions

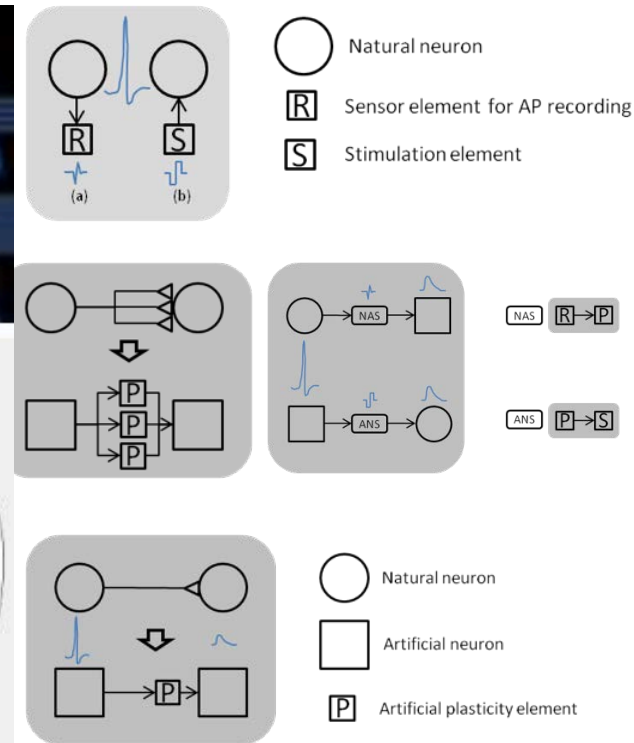
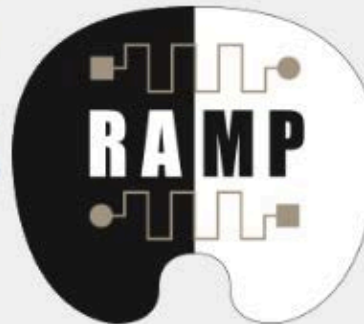
Development of real biohybrid platforms



RAMP project

Information processing in classical *von Neumann* architectures is less efficient compared to biological counterparts when dealing with ill-posed problems and noisy data.

The reason is that the biological brain is configured differently and the key is its evolving structure, where connectivity elements between individual neurons, the synapses, undergo *birth* and *death* as well as strengthening and weakening through a selection process, reconfiguring neuronal connectivity in a self-organizing manner and allowing the networked population of neuronal processors to adapt motor and behavioural responses to the ever changing environment.

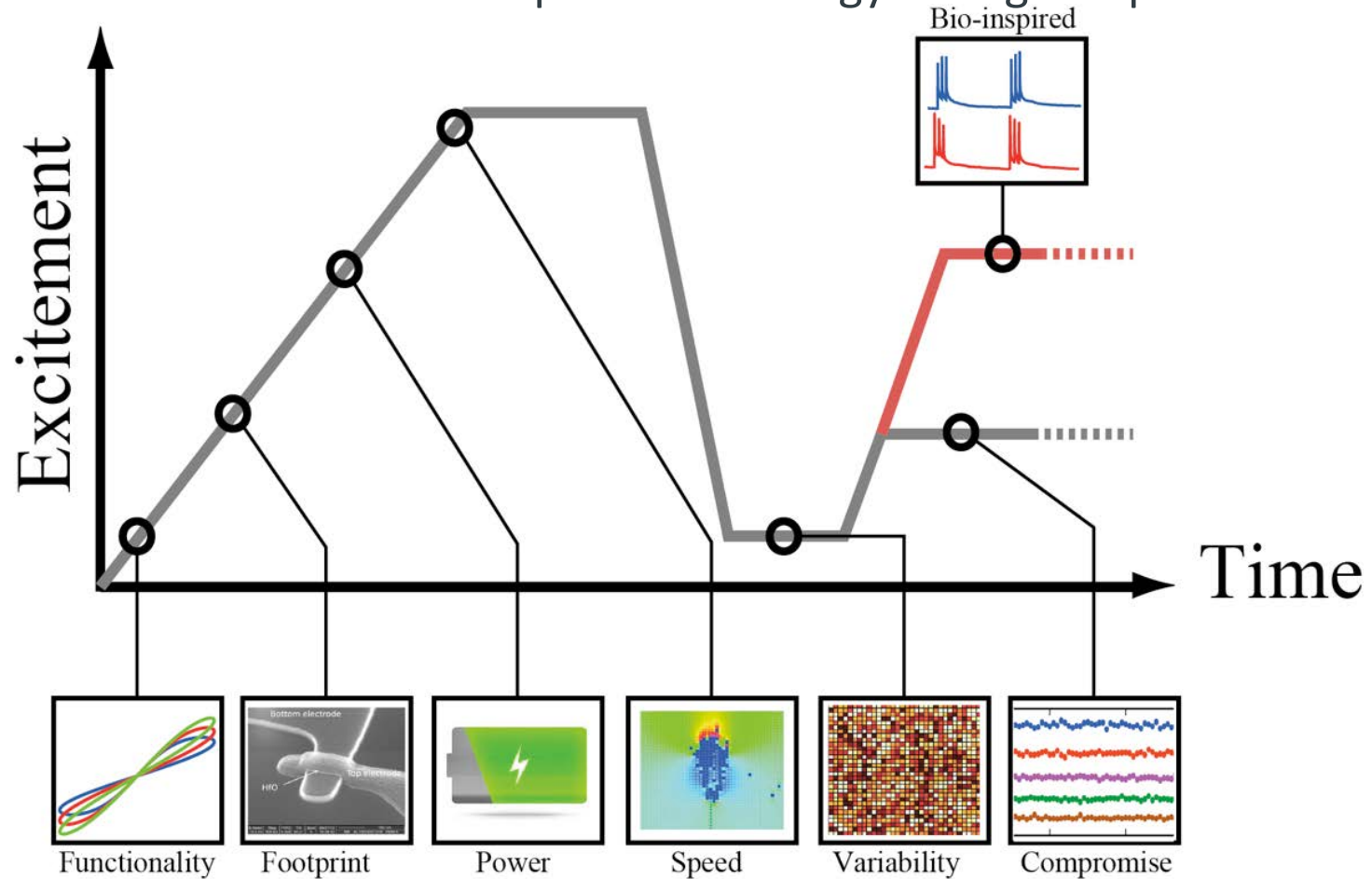


<http://www.cyberrrat.eu/ramp>

FP7, “Real neurons-nanoelectronics Architecture with Memristive Plasticity”, €2.1M, Nov 2013

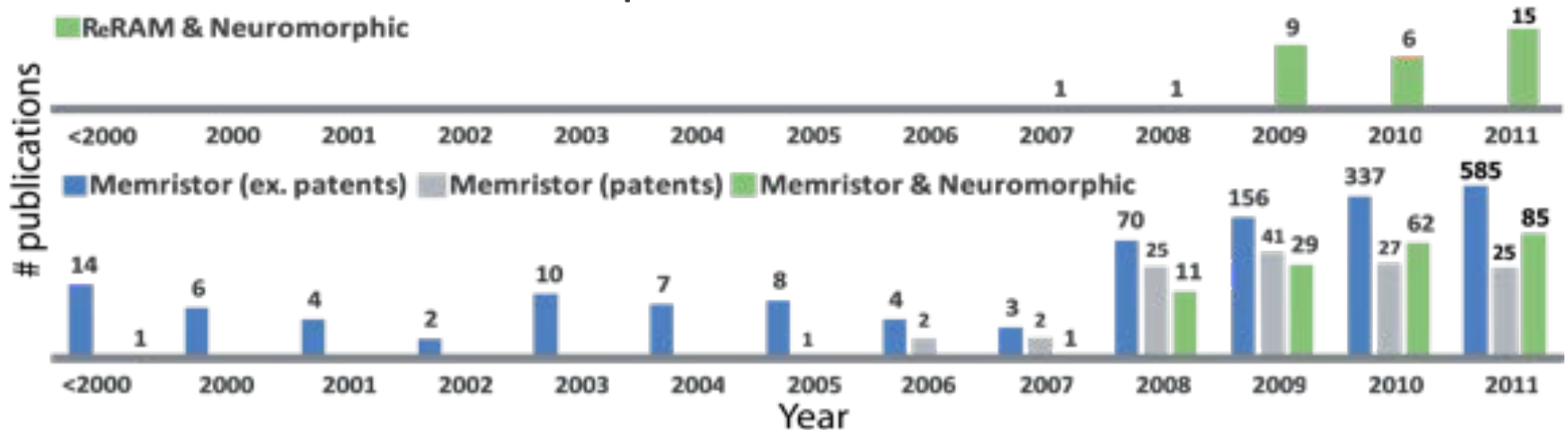
Conclusion

Memristors are a disruptive technology with great potential



Conclusion

A new era: Brain-inspired electronics with Memristors



The proposed technology opens the possibility of attaining programmable cells of **minimal size-/power-requirements**, without undermining **biological fidelity**, for those elements that are most numerous: **synaptic connections**.

Feynman: “What I cannot create, I do not understand”

Acknowledgements

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Questions???

t.prodromakis@soton.ac.uk