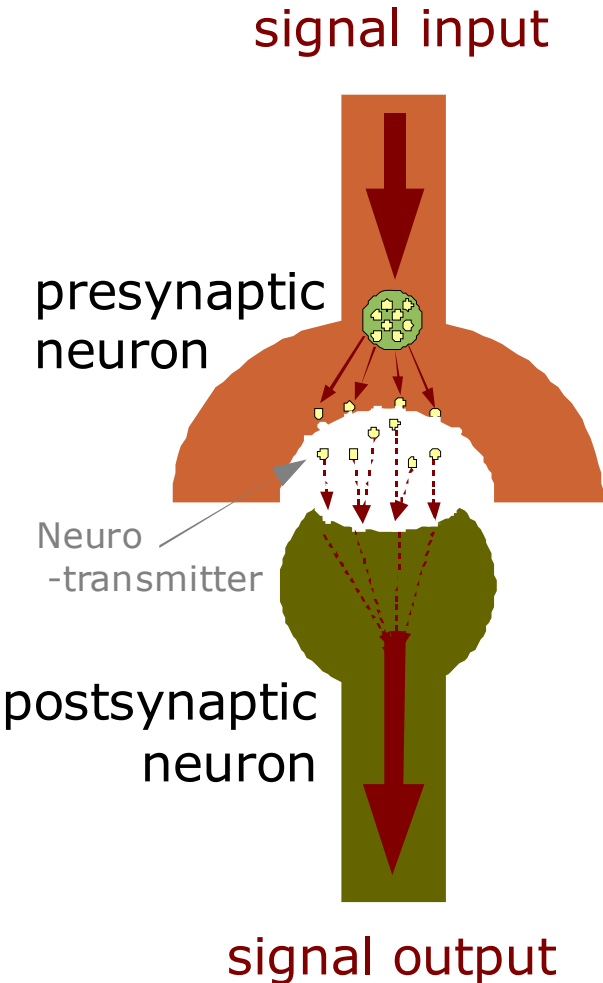


Demonstration of implicate memory in electronic circuits by using memresistive devices

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Neurotransmission: synaptic decoding

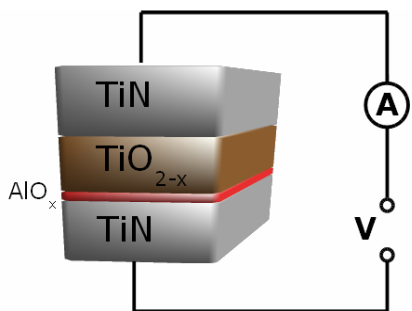


reception coding transmission

- information is **analogue** encoded in synapses

biological	electronic
Duration +Intensity	Pulse width +Signal height
Neurotransmitter concentration	Resistive state of the device

Memristive Devices for Neuromorphic Systems

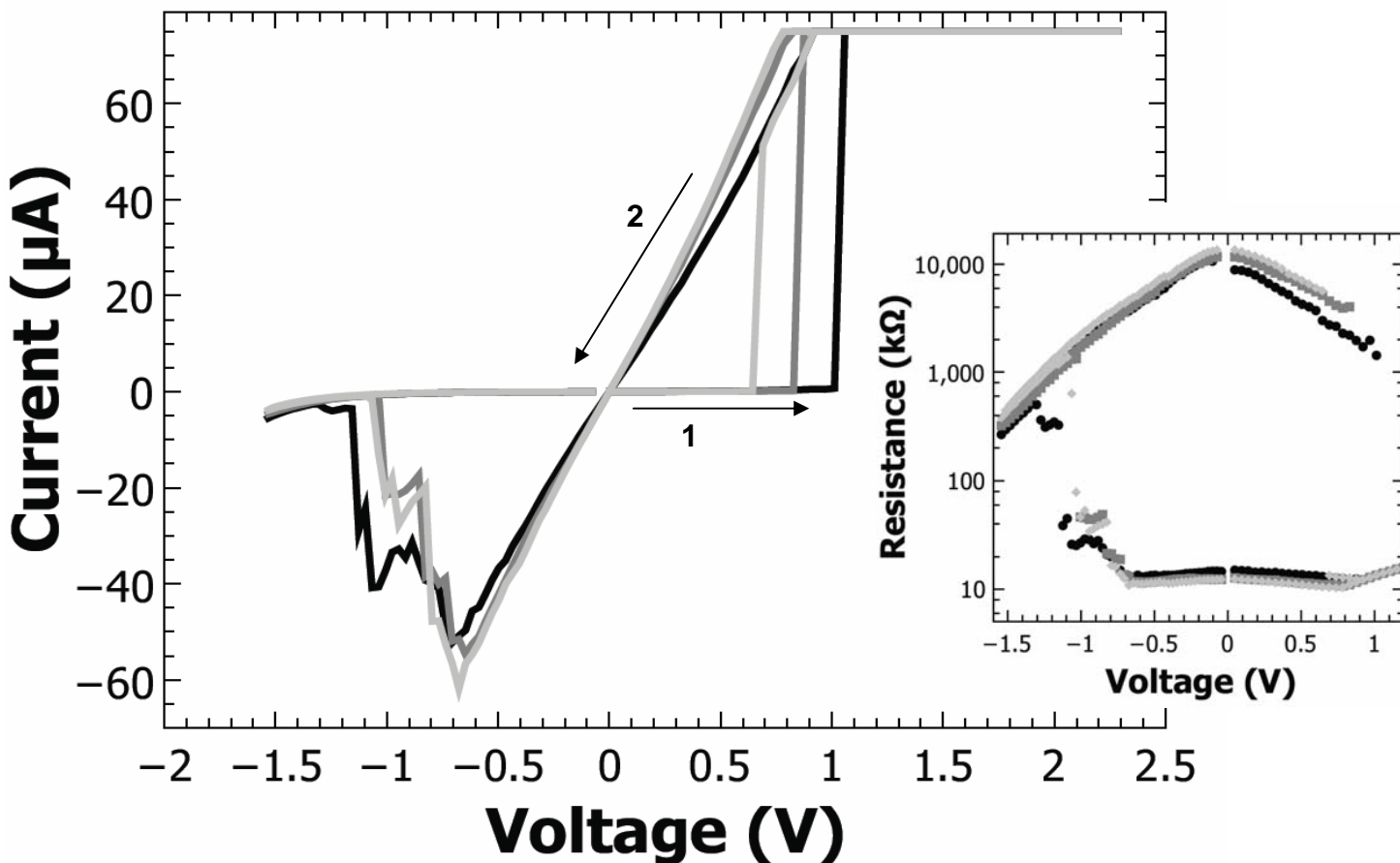


- memristive devices must exhibit a **threshold voltage**

M. Ziegler et al., Adv. Func. Mat. (2012).

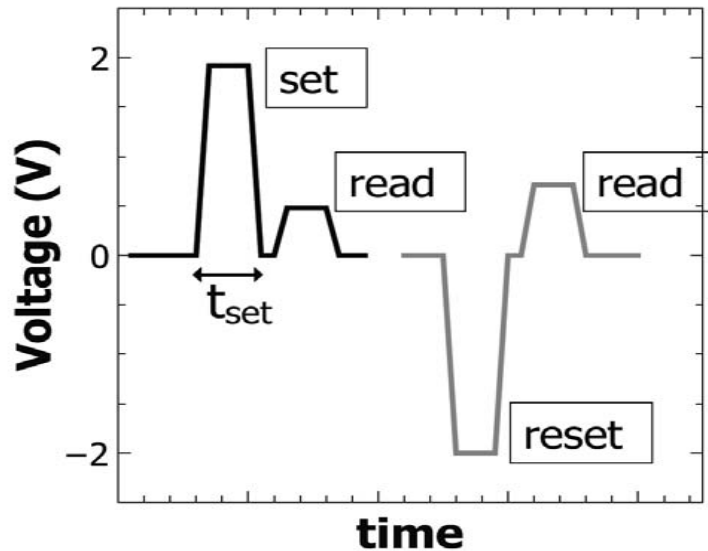
- for dense arrays a **low power consumption** is needed

C. Zamarreño-Ramos et al., Front. Neurosci. 5, 26 (2011).



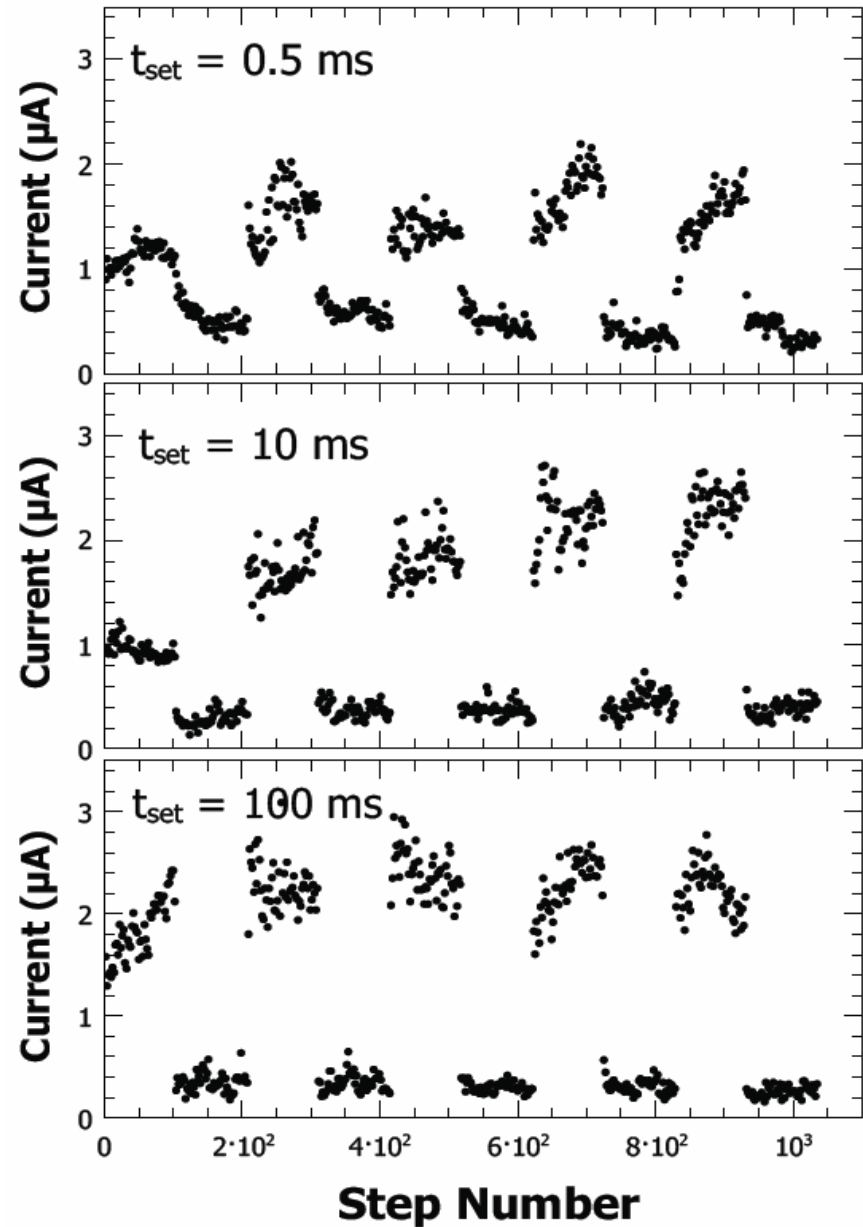
Synaptic potentiation

Sung Hyun Jo et al., *Nano Lett.* **10**, 1297-1301 (2010).
T. Ohno et al., *Nature Materials* **10**, 591-595 (2011).



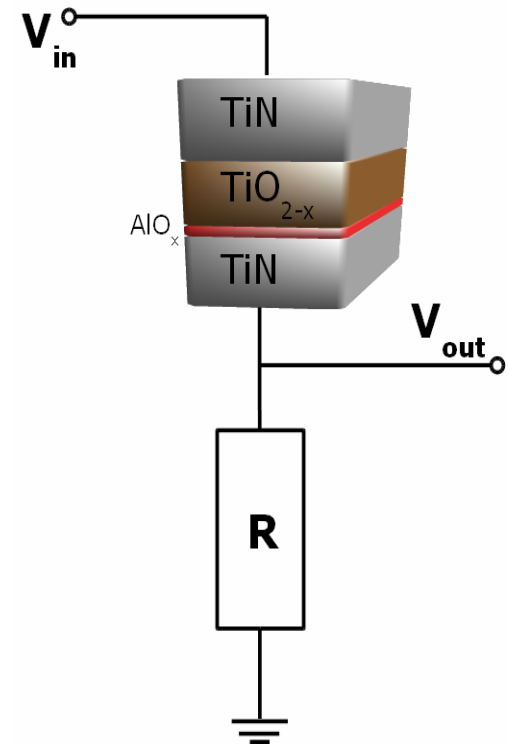
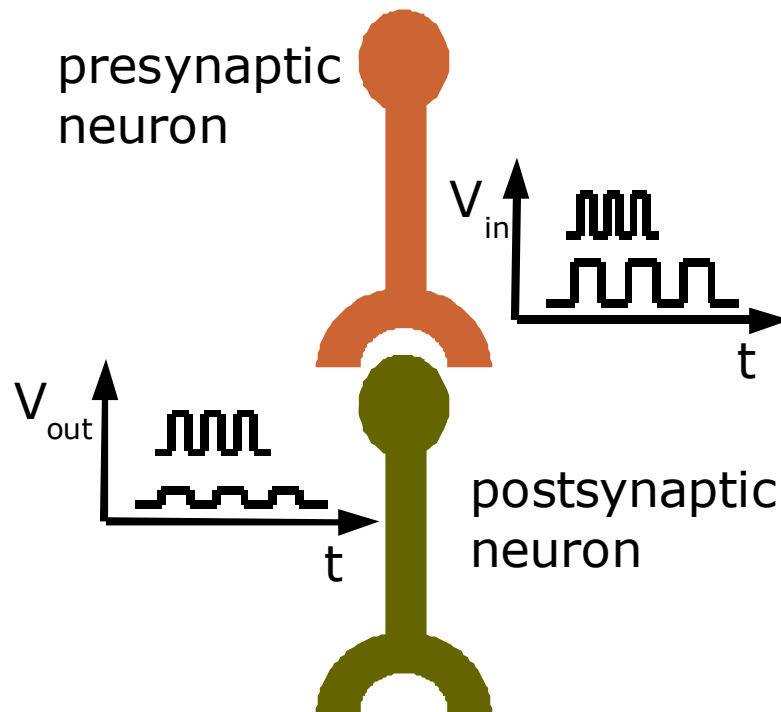
- **neural plasticity** can be mimicked by voltages pulses with different **voltage amplitude** and **pulse width**

➔ **Neurotransmission?**



Neural mediating circuit

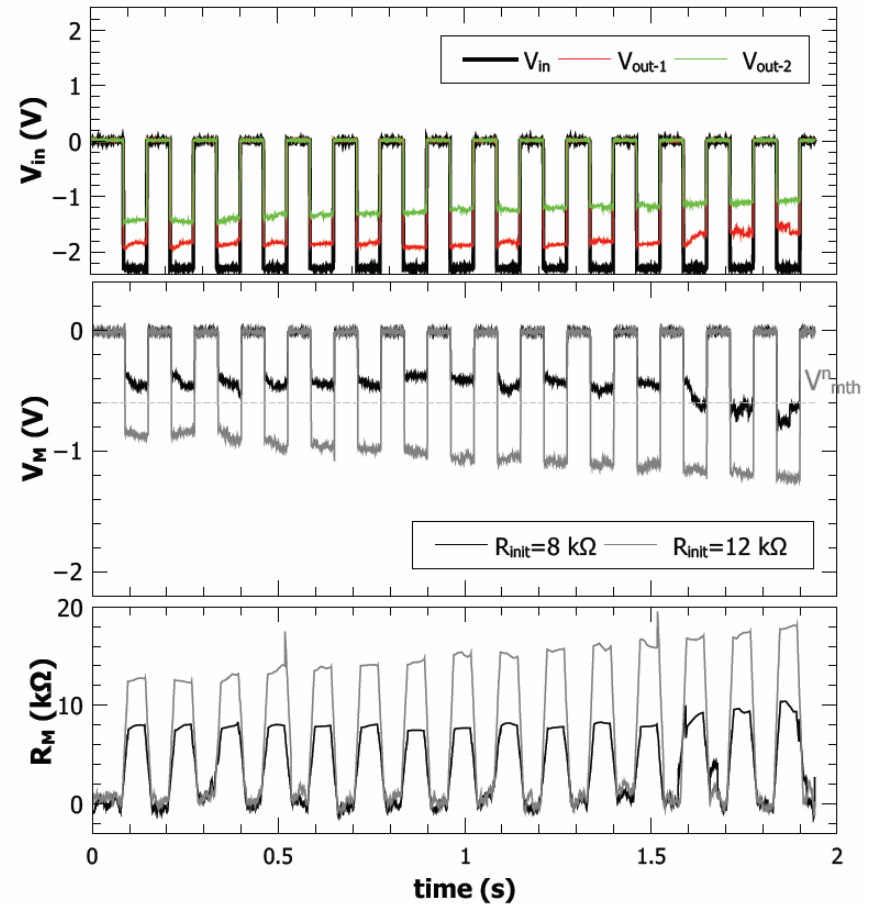
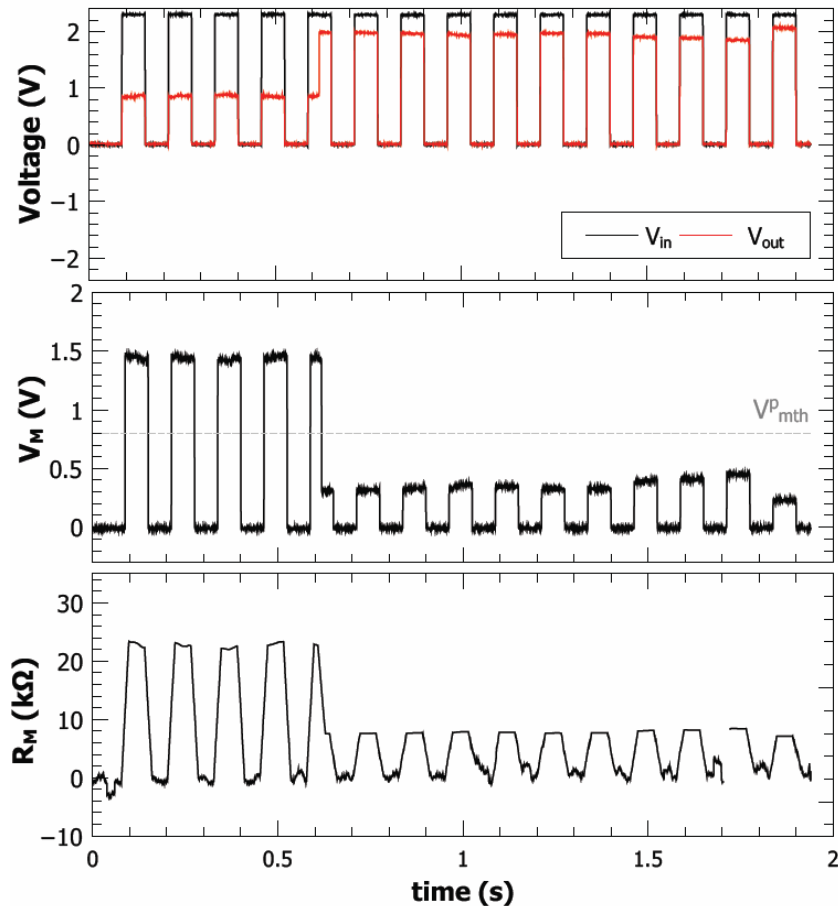
- **Post-synaptic potential (PSP)** is mimicked within a memristive cell forming a voltage divider in combination with a linear $10\text{ k}\Omega$ resistor.



Neurotransmission in an electronic circuit

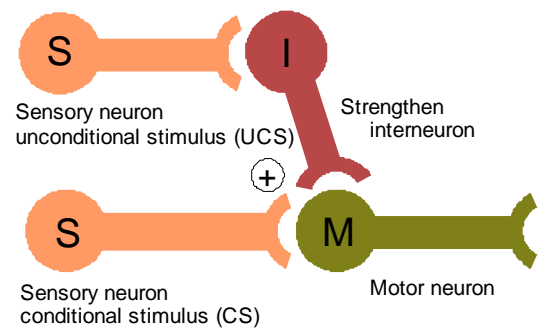
- **synaptic plasticity** mimicked with pos. and neg. voltages pulses

M. Ziegler et al., Adv. Func. Mat. (2012).

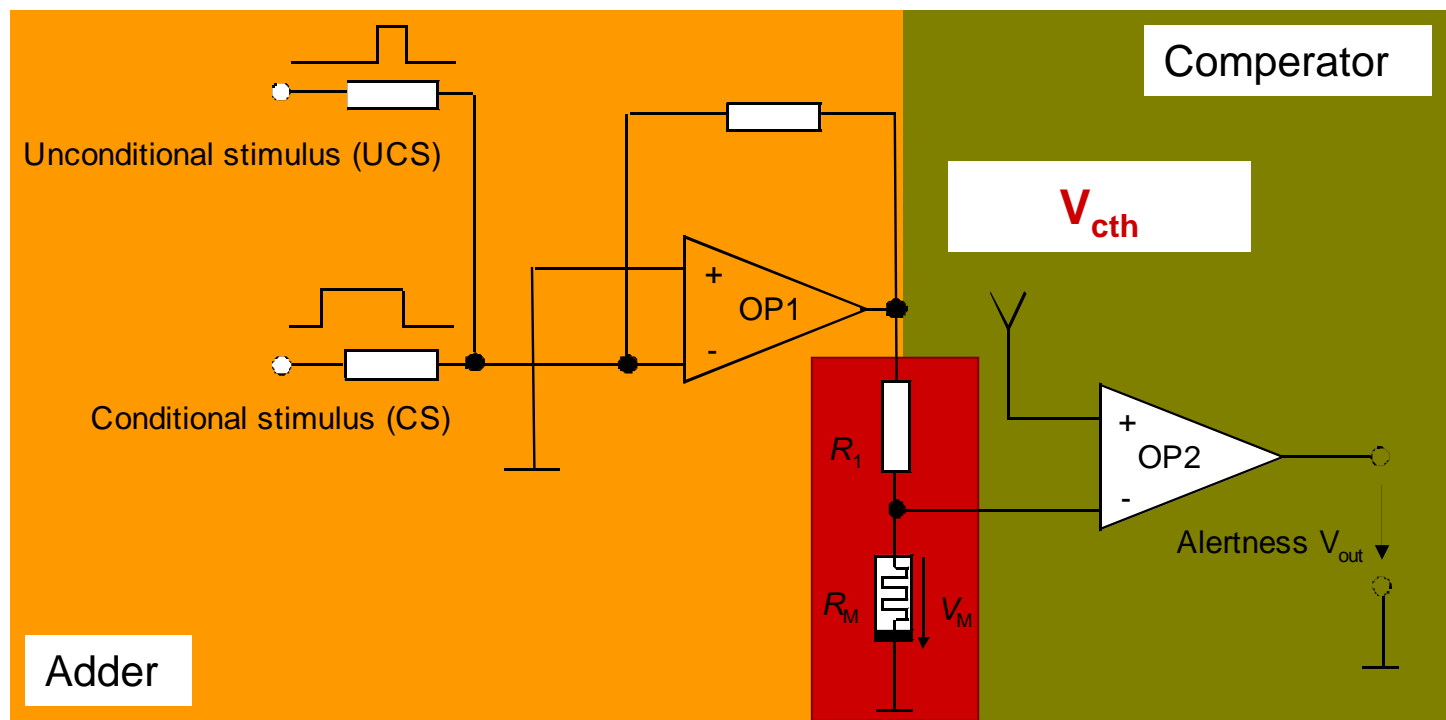


Neural mediating circuit for associative learning

- Electrical circuit layout: single memristive device implemented in an analogue circuitry



M. Ziegler et al., Adv. Func. Mat. (2012).



- **Voltage divider** compromising a memristive device

Conclusions

Demonstration of implicit memory in electronic circuits by using memresistive devices

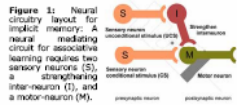
M. Ziegler, M. Hansen, and H. Kohlstedt



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E-mail: maz@tf.uni-kiel.de

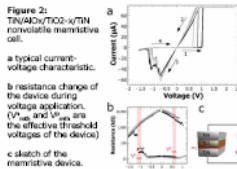
Implicit memory

For biological systems Eric Kandel was able to get access to the fundamentals of learning and memory by applying a radical reductionistic strategy.[1] At this, the principles of implicit memory in mammal brains can be understood on the cellular level, where learning alters the function and structure of neurons and their interconnection strength.



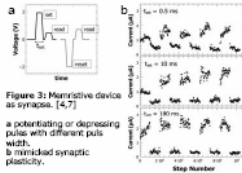
Memristive Device

Memristive cells for neuromorphic systems: To be a realistic substitute for basic building blocks in nerve cells, the memristive device must exhibit a threshold voltage. [3] For implementations of dense arrays, memristive cells with low power consumption are needed. [2,3]



Synaptic potentiation

Neural plasticity on a cellular level occurs by morphological changes in the synaptic connections causing synaptic facilitation (sensitization) or synaptic depression (habituation). [1,5]



Neurotransmission: synaptic decoding for inter-neuronal information transmission the stimulus information is analogue encoded.

biological	electronic
Excitation = intensity	Pulse width = signal height
Neuro-transmitter concentration	Has stable state (voltage divider)

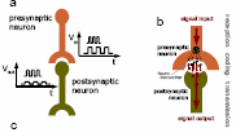


Figure 4: Information transmission in a neural circuit: a) neural mediating circuit, b) inter-neural analogue information coding, c) electronic version of inter-neuronal information transmission.

Post-synaptic potential (PSP) is mimicked within a memristive cell forming a voltage divider in combination with a linear 10 kΩ resistor.

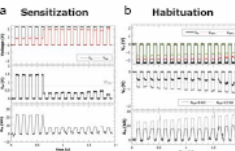


Figure 5: Synaptic plasticity mimicked with positive and negative voltage pulses. a) Sensitization: Voltage pulses above V_{th} leads to a depression of the device resistance. b) Habituation: Voltage pulses below V_{th} enhancing the device resistance.

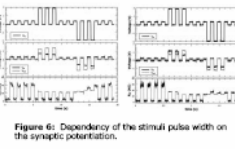


Figure 6: Dependency of the stimuli pulse width on the synaptic potentiation.

STM to LTM: synaptic coupling strength Asymmetry function are used to describe the synaptic coupling strength. [3]

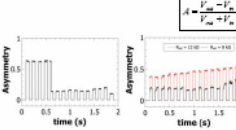
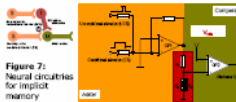


Figure 6: Resistance dependent asymmetries

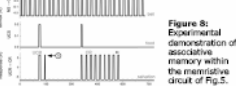
Neural circuitry layout

Neural circuitry layouts consists of a signal adder, a voltage divider comprising a memristive cell and a linear ohmic resistor, and a comparator. [3]



Pavlov's dog

An electronic version of Pavlov's dog [3]: If the neutral stimulus V_{NS} merges the unconditional stimulus V_{US} the resistance of the system is enhanced. After two sequences the circuitry learned to associate V_{NS} with that of V_{US} , affecting an output of the comparator (response of the dog). [3,6,8]



Conclusion

- Neurobiological phenomena of learning can be translated and emulated with a memristive device
- Memristive devices must exhibit a threshold voltage to be considered as a realistic substitute for basic building blocks in nerve cells

References:
[1] E. R. Kandel, Cellular basis of behavior: introduction to behavioral neurobiology, W. H. Freeman and Company, San Francisco, 2006.
[2] M. Ziegler, M. Hansen and H. Kohlstedt, *Adv. Phys. Chem.*, **10**, 100 (2016).
[3] M. Ziegler et al., *Adv. Phys. Chem.*, **10**, 100 (2016).
[4] S. H. Lee et al., *IEEE Trans. Nanotechnol.*, **10**, 100 (2011).
[5] E. R. Kandel, *The Principles of Learning and Memory*, New York, 1998.
[6] D. O. Hebb, *Organization of Behavior*, Wiley, New York, 1949.
[7] D. O. Hebb, *Organization of Behavior*, Wiley, New York, 1949.
[8] *Experimental Psychology and Psychobiology in Animals*, vol. 1, p. 47-65, 1967.
[9] *Psychic Instincts in Conditional Reflexes*, International Publ., New York, 1967.
[10] V. A. Pavlov, *Adv. Phys. Chem.*, **10**, 100 (2016).

• Neurobiological phenomena of learning can be translated and emulated with a single memristive device.

• effective threshold voltages and device resistances are fundamental design parameters.

• ... more on the poster

Thanks for your attention!

