



**HAL**  
open science

## Energy Efficient Neuromorphic Computing with beyond-CMOS Oscillatory Neural Networks

Corentin Delacour, Stefania Carapezzi, Gabriele Boschetto, Aida Todri-Sanial

► **To cite this version:**

Corentin Delacour, Stefania Carapezzi, Gabriele Boschetto, Aida Todri-Sanial. Energy Efficient Neuromorphic Computing with beyond-CMOS Oscillatory Neural Networks. ICONS 2021 - International Conference on Neuromorphic Systems, Jul 2021, Oak Ridge (Virtual), United States. lirmm-03229262

**HAL Id: lirmm-03229262**

**<https://hal-lirmm.ccsd.cnrs.fr/lirmm-03229262v1>**

Submitted on 22 Sep 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Energy Efficient Neuromorphic Computing with beyond-CMOS Oscillatory Neural Networks

Corentin Delacour, Stefania Carapezzi, Gabriele Boschetto and Aida Todri-Saniai\*

## ABSTRACT

Oscillatory Neural Networks (ONNs) are non-von Neumann architectures where information is encoded in phase relations between coupled oscillators. In this work, we present the concept of ONN based on beyond-CMOS devices to reduce the energy footprint of neuromorphic circuits. We investigate oscillating neurons made of vanadium dioxide material ( $\text{VO}_2$ ) and synapses based on molybdenum disulfide ( $\text{MoS}_2$ ) memristors to emulate synaptic plasticity.

## KEYWORDS

ONN, Neuromorphic circuit, Beyond-CMOS,  $\text{VO}_2$ ,  $\text{MoS}_2$  Memristor

## 1 COMPUTING IN PHASE

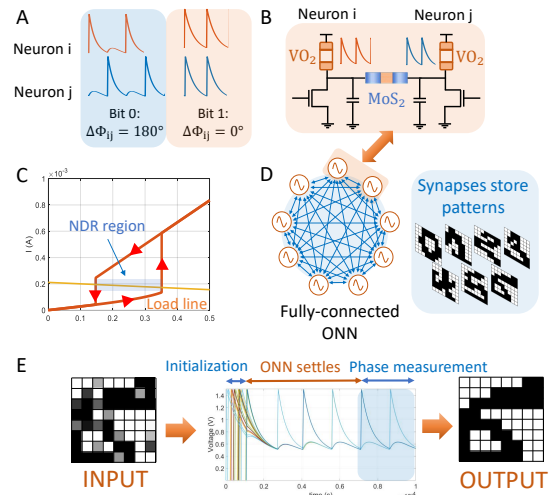
ONN encodes information in phase relations between synchronized analog oscillating circuits (Fig.1A) interconnected by electrical components to emulate synapses (Fig.1B). ONN is a non-linear system where synaptic currents flow in parallel through the network to achieve high-speed computing. Computing with ONN consists of 1) setting an initial phase state, 2) letting the ONN settle, and 3) measuring the final phases with respect to a reference (first oscillator) [1]. Inference efficiency is of interest for edge devices with limited power and memory resources that run AI algorithms.

## 2 ONN DESIGN FROM DEVICES, CIRCUITS TO ARCHITECTURE

Beyond-CMOS devices based on  $\text{VO}_2$  and  $\text{MoS}_2$  materials allow compact and configurable ONN circuit design using few components for low energy operations [2]. We harness phase change transitions of  $\text{VO}_2$  material to design compact relaxation oscillators [2]. We bias a two-terminal  $\text{VO}_2$  device with a transistor in series, such that the load line intercepts the  $\text{VO}_2$  Negative Differential Resistive (NDR) region to produce oscillations (Fig.1.C). For large scale ONNs, we couple oscillators with  $\text{MoS}_2$  memristors (Fig.1.B) to emulate synaptic plasticity from weak coupling (large  $\text{MoS}_2$  resistance) to strong coupling (small  $\text{MoS}_2$  resistance).

## 3 IMAGE RECOGNITION WITH ONN

By associating oscillator  $i$  to a single pixel, one can interpret ONN phase state as a binary image where  $\Delta\Phi_i = 0^\circ$  and  $\Delta\Phi_i = 180^\circ$  correspond to a white and a black pixel, respectively [1]. When oscillators are fully connected like in Hopfield Neural Networks [3] (Fig.1D), ONN associates a noisy input to a stored image for recognition. We train the ONN using the Hebbian rule [1], and we map synaptic coefficients to coupling resistances implemented



**Figure 1:** A) Phase encodes information in ONN. B) Two  $\text{VO}_2$ -oscillators coupled by a  $\text{MoS}_2$  memristor. C)  $\text{VO}_2$  IV curve and load line in the NDR region to obtain oscillations. D) ONN in a fully-connected network as a HNN. E) Example of 8x8 ONN inference.

by  $\text{MoS}_2$  memristors [4]. For ONN inference, we apply a noisy input image, and we run transient circuit simulations (described in [4] and [5]). ONN settles to the correct state in only 4 cycles in average and associates the input image to one of the stored patterns (Fig.1E). With  $\text{VO}_2$  oscillators running at 20 MHz and @ 0.3 V supply voltage [2], an image recognition task would dissipate  $4 \times 50$  fJ/neuron/oscillation = 200 fJ/neuron, which is 6x less than state-of-the-art ONN in 28 nm CMOS technology [6].

## 4 CONCLUSION

We have showcased a beyond-CMOS ONN composed of  $\text{VO}_2$  neurons and  $\text{MoS}_2$  synapses. Circuits compactness and ONN parallelism bring a promising alternative to the von-Neumann architecture for real-time AI workloads such as image recognition at the edge.

## REFERENCES

- [1] F.C. Hoppensteadt and E.M. Izhikevich, "Pattern recognition via synchronization in phase-locked loop neural networks," IEEE Trans. Neural Netw., vol. 11, 2000.
- [2] E. Corti et al., "Coupled  $\text{VO}_2$  Oscillators Circuit as Analog First Layer Filter in Convolutional Neural Networks", Frontiers in Neuroscience, vol. 15, 2021.
- [3] J.J. Hopfield, "Neural networks and physical systems with emergent collective computational abilities," Proc. Natl. Acad. Sci. U.S.A., vol. 79, pp. 2554–2558, 1982.
- [4] C. Delacour and A. Todri-Saniai, "Mapping Hebbian Learning Rules to Coupling Resistances for Oscillatory Neural Networks", working paper or preprint, <https://hal-lirmm.ccsd.cnrs.fr/lirmm-03197299>, 2021.
- [5] A. Todri-Saniai et al., "How Frequency Injection Locking Can Train Oscillatory Neural Networks to Compute in Phase", working paper or preprint, <https://hal-lirmm.ccsd.cnrs.fr/lirmm-03164135>, 2021.
- [6] T. Jackson et al., "An oscillatory neural network with programmable resistive synapses in 28 nm CMOS," 2018 IEEE International Conference on Rebooting Computing (ICRC), pp. 1–7, 2018.

\*C. Delacour, S. Carapezzi, G. Boschetto and A. Todri-Saniai are with the Microelectronics Department, LIRMM, University of Montpellier, CNRS, Montpellier, France, e-mail: corentin.delacour@lirmm.fr.

This work was supported by the European Union's Horizon 2020 research and innovation program, EU H2020 NEURONN (www.neuronn.eu) project under Grant 871501.