# Percolating Nanoparticle Networks for Neuromorphic Computing

A.J.T. Van der Ree[(1,2)], M. Ahmadi[(1)], G.H. Ten Brink[(1)], B.J. Kooi[(1)], G. Palasantzas[(1)]

(1) Zernike Institute for Advanced Materials, University of Groningen, 9747 AG Groningen, The Netherlands
(2) CogniGron Center, University of Groningen, 9747 AG Groningen, The Netherlands

Conventional computing architectures, despite their astounding success in modern world technology, are facing their fundamental limitations. Neuromorphic or 'brain-like' computing seeks to overcome aforementioned limitations by physically emulating the neuronal and synaptic building blocks of the energy efficient[1,2], mammalian brain at the device level.

Percolating nanoparticle (NP) networks have recently emerged as an alternative to neuromorphic computing systems. They exhibit electrical spiking signals upon biasing comparable to networks of biological neurons[3]. This behavior has been attributed to the vast amount of tunneling gaps and filamentary bridging of said tunneling gaps between well- and poorly connected clusters of NPs.

Gold, tin, bismuth and silver have been the constituents of the NP networks so far, all showing similar synaptic behavior[4–8] but at significantly higher voltages ($> 1$V) making their implementation for low power consumption requirements rather unsuitable.

Here, we compare percolating molybdenum and copper NP networks, both capable of room temperature, resistive switching at applied biases as low as 1 mV and explore reasons to why these materials exhibit switching at all, but also why they possess significantly lower switching thresholds compared to previously studied materials. We will also discuss how the experimental setups have been created and designed. By performing in-situ electrical measurements to both, reach criticality and, perform long-duration measurements at sub-50 mV biases, we reveal neuristive switching behavior. Furthermore, utilizing electron microscopy techniques, the switching behavior has been visualized.

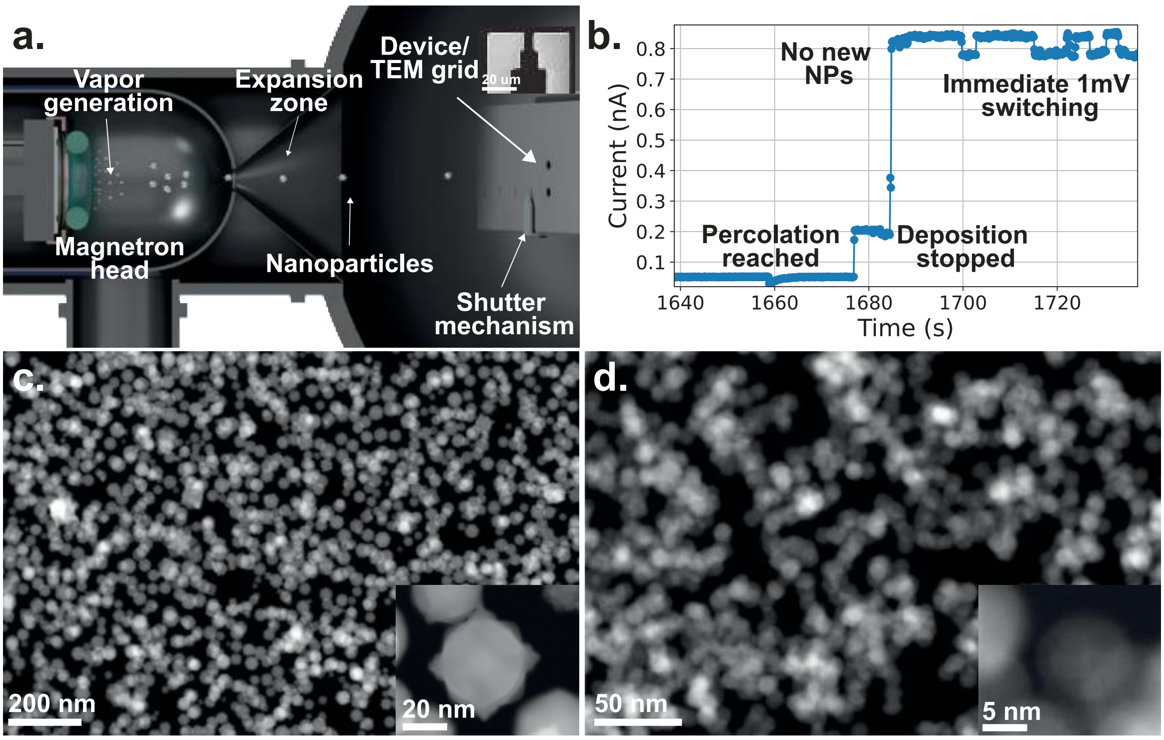


Figure 1: **a.** Shows schematically NP production via gas-phase synthesis. Utilizing a magnetron sputterer and an aggregation chamber, NPs can be produced and deposited onto an electrically monitored, (scanning) transmission electron microscopy ((S)TEM)-compatible chip as seen in the inset. In **b.** the electrical conductivity of the chip is monitored such that the point of percolation can be identified(first substantial rise in conductivity) and halt the deposition. Note the immediate switching under a 1 mV bias after halting the deposition. A pristine size and deposition rate control yields a percolating network of homogeneously sized molybdenum and copper NPs seen in, **c.** and **d.** respectively, the high angular annular dark field (HAADF) (S)TEM images.

[1] J. J. Harris, R. Jolivet, and D. Attwell. “Synaptic Energy Use and Supply”. In: *Neuron* 75 (5 Sept. 2012), pp. 762–777. ISSN: 0896-6273. DOI: 10.1016/J.NEURON.2012.08.019.

[2] V. Balasubramanian. “Brain power”. In: *Proceedings of the National Academy of Sciences of the United States of America* 118 (32 Aug. 2021). ISSN: 10916490. DOI: 10.1073/pnas.2107022118.

[3] S. Shirai, S. K. Acharya, S. K. Bose, J. B. Mallinson, E. Galli, et al. “Long-range temporal correlations in scale-free neuromorphic networks”. In: *Network Neuroscience* 4 (2 Apr. 2020), pp. 432–447. ISSN: 24721751. DOI: 10.1162/NETN_A_00128.

[4] J. Schmelzer, S. A. Brown, A. Wurl, M. Hyslop, and R. J. Blaikie. “Finite-Size Effects in the Conductivity of Cluster Assembled Nanostructures”. In: *Physical Review Letters* (2002). DOI: 10.1103/PhysRevLett.88.226802.

[5] S. Fostner and S. A. Brown. “Neuromorphic behavior in percolating nanoparticle films”. In: *PHYSICAL REVIEW E* 92 (2015), p. 52134. DOI: 10.1103/PhysRevE.92.052134.

[6] S. K. Bose, J. B. Mallinson, R. M. Gazoni, and S. A. Brown. “Stable Self-Assembled Atomic-Switch Networks for Neuromorphic Applications”. In: *IEEE Transactions on Electron Devices* 64 (12 Dec. 2017), pp. 5194–5201. ISSN: 00189383. DOI: 10.1109/TED.2017.2766063.

[7] M. Mirigliano, D. Decastri, A. Pullia, D. Dellasega, A. Falqui, et al. “Complex electrical spiking activity in resistive switching nanostructured Au two-terminal devices”. In: *Nanotechnology* (2020). DOI: 10.1088/1361-6528/ab76ec.

[8] N. Carstens, B. Adejube, T. Strunskus, F. Faupel, S. Brown, et al. “Brain-like critical dynamics and long-range temporal correlations in percolating networks of silver nanoparticles and functionality preservation after integration of insulating matrix †”. In: *Nanoscale Advances* (2022). ISSN: 2516-0230. DOI: 10.1039/d2na00121g.