In Situ Study of Self-Organized Memristive Switching in Neuromorphic Nanoparticle Networks using Complementary SEM Methods

Ole Gronenberg[1], Mrs. Blessing Adejube[2], Mr. Torben Hemke[3], Dr. Niko Carstens[3], Mr. Oguz Han Asnaz[4], Dr. Ulrich Schürmann[1,6], Dr. Thomas Strunskus[2,6], Dr. Franz Faupel[2,6], Dr. Thomas Mussenbrock[3], Dr. Jan Benedikt[4,6], Dr. Alexander Vahl[2,5,6], Dr. Lorenz Kienle[1,6]
[1]Department of Materials Science – Synthesis and Real Structure, Faculty of Engineering, Kiel University, Kiel, Germany, [2]Department of Materials Science – Chair for Multicomponent Materials, Faculty of Engineering, Kiel University, Kiel, Germany, [3]Chair of Applied Electrodynamics and Plasma Technology (AEPT), Ruhr University Bochum, Bochum, Germany, [4]Experimental Plasma Physics, Institute of Experimental and Applied Physics, Kiel University, Kiel, Germany, [5]Leibniz Institute for Plasma Science and Technology, Greifswald, Germany, [6]Kiel Nano Surface and Interface Science KiNSIS, Kiel University, Kiel, Germany

Background incl. aims
Self-organized nanoparticle networks (NPNs) poised at the percolation threshold are promising for bio-inspired information processing. These networks show non-linear responses, high dimensionality and avalanche dynamics similar to those observed in the brain. The objective of this study is the imaging of the current path through the NPN to study the distributed memristive switching events.

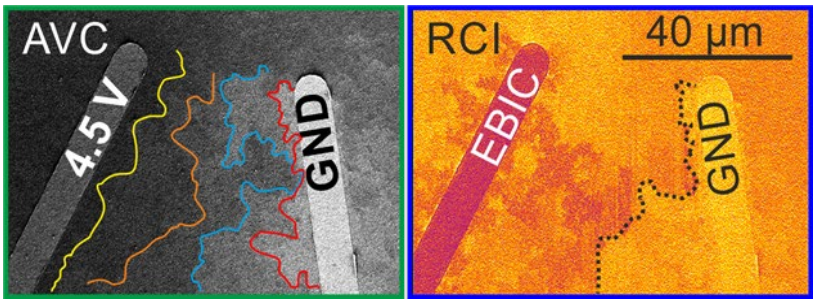
Methods
The neuromorphic NPN was fabricated in two steps. First, an insulating base-layer, consisting of Ag NPs with a CxOyHz shell, was deposited on pre-structured Pt electrodes on a Si chip with 1 µm thermal oxide. In a second deposition step, pure Ag NPs were deposited under continuous conductance monitoring until the percolation threshold was reached. The avalanche dynamics of the NPN with features of criticality were analyzed ex situ. Ultimately, this NPN was analyzed in the SEM (FEI Helios Nanolab 600 SEM/FIB with a field emission gun operated at 3 kV) with 2 complementary methods. First, during in operando biasing a changing active voltage contrast (AVC) was observed. Second, resistive contrast imaging (RCI) revealed directly the current path after biasing steps. For these experiments, Pt electrodes below the NPN were electrically connected in situ by micromanipulators with tungsten needles to an EBIC amplifier from Kleindiek company. To gain a better understanding of the current response of NPNs, we corroborate the experimental results with kinetic Monte-Carlo simulations.

Results
After biasing, RCI was used to observe directly the current path (see graphic) revealing changes in the connectivity after successive biasing steps, while the overall morphology of NP groups persisted. AVC revealed a step-like potential distribution (see graphic) that changed during static biasing. Simulations indicated that nano-gaps between NP groups lead to the step-like potential distribution that varies due to switching events.

Conclusion
Current path imaging using AVC and RCI indicates that the current path changes steadily during biasing due to the construction and deconstruction of memristive filaments in nano-gaps between NP groups. The changing position of the nano-gaps is highlighted by strong resistive contrast. Thus, we correlated the avalanche dynamics of the NPN with spatio-temporally distributed resistive switching events within the network with the complementary combination of AVC and RCI.

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 434434223 – SFB 1461

Graphic:



Keywords:

Resistive-Contrast-Imaging, Active-Voltage-Contrast, Neuromorphic, Memristor, Self-Organization

Reference:

1 N. Carstens, B. Adejube, T. Strunskus, F. Faupel, S. Brown, A. Vahl, Nanoscale Adv. 2022, 4, 3149.

2 O. Gronenberg, B. Adejube, T. Hemke, J. Drewes, O. H. Asnaz, F. Ziegler, N. Carstens, T. Strunskus, U. Schürmann, J. Benedikt, T. Mussenbrock, F. Faupel, A. Vahl, L. Kienle, Adv Funct Mater 2024.