Materials Horizons

EDITORIAL

Cite this: DOI: 10.1039/d4mh90052a

Introduction to memristors and neuromorphic systems

Xiaodong Chen,[a] Cheol Seong Hwang,[b] Yoeri van de Burgt[c] and Francesca Santoro[def]

DOI: 10.1039/d4mh90052a

rsc.li/materials-horizons

Recent generative artificial intelligence (AI) has exerted a profound and far-reaching global impact across diverse fields and society. However, it comes at the cost of substantial energy and computational resource consumption. Neuromorphic computing endeavors to create highly efficient computing hardware that emulates biological neural networks and even mimics some human brain functions, and it is expected to play an essential role in the next-generation computing hardware. Memristors open up novel opportunities for neuromorphic computing due to their feasible ability to mimic neural functions. Innovation in memristors may lead to novel algorithms and contribute to conventionally challenging tasks like nondeterministic polynomial time (NP)-hard problem. To this end, we present a themed collection in *Materials Horizons* and *Nanoscale Horizons*, in which we publish the latest developments in memristive materials, device fabrication, characterization, and circuit design for neuromorphic systems.

The current AI models have made remarkable strides in diverse fields like computer vision and natural language processing, while running on a digital von Neumann computer, although this architecture is proven more and more to be inefficient. Due to the increasing computing demand for big-data applications, traditional von Neumann architectures face the significant challenge of continuous data transfer between separate processors and memory units, which invokes high energy consumption issues. Over long evolution, the human brain has become a highly efficient intelligent platform featured by complex neural architecture and advanced cognitive functions. Inspired by the brain, neuromorphic computing aims to realize efficient computing resources by mimicking biological neural networks.[1] Memristors, discovered as the fourth basic circuit element in 1971,[2] have garnered significant attention and enthusiasm within the context of neuromorphic devices that emulate synaptic and neuronal functions.[3] Memristors exhibit significant potential for the hardware implementation of highly efficient artificial neural networks[4,5] and biomimetic robotics.[6]

This themed collection includes outstanding contributions in memristors and neuromorphic systems, highlighting the latest memristor development in memristive materials, device fabrication, and circuit design for future neuromorphic and in-memory computing systems. Memristive materials are the foundation for high-performance memristor-based neural networks. Solanki's group reported a solution-processed lead-iodide-based flexible memristive device (**https://doi.org/10.1039/d3nh00505d**). The device demonstrates unique features like low operation voltage (<1.0 V), high stability (2×10^4 cycles of potentiation and depression), and synaptic characteristics (short and long-term plasticity and spike time-dependent plasticity) on a flexible substrate. The flexible platform demonstrates exceptional performance, achieving 95.1% simulated recognition accuracy of the handwritten dataset. This work offers profound insights into low-cost device fabrication techniques, which will be essential in the practical application of memristors. Casiraghi's group developed a fully printed memristor device, where MoS_2 is printed as a resistive switching material, while graphene and silver are printed as top and bottom electrodes, respectively (**https://doi.org/10.1039/d3mh01224g**). The device fabricated on Kapton film exhibits resistance switching ratios of 10^2–10^3 and remains stable at least up to 2% of strain. The work shows that inkjet printing is a feasible and flexible memristor fabrication technology. Hardware implementation of efficient neural networks based on memristors is an important step towards the practical use of memristors. Hwang's group reported a reservoir computing neural network based on heterogeneous Ta_2O_5/HfO_2 memristors (**https://doi.org/10.1039/d3nh00493g**). The heterogeneous reservoir states are

[a] *Innovative Centre for Flexible Devices (iFLEX), Max Planck–NTU Joint Lab for Artificial Senses, School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore. E-mail: chenxd@ntu.edu.sg*
[b] *Department of Materials Science and Engineering and Inter-university Semiconductor Research Center, College of Engineering, Seoul National University, Seoul, 08826, Republic of Korea. E-mail: cheolsh@snu.ac.kr*
[c] *Microsystems and Institute for Complex Molecular Systems, Eindhoven University of Technology, Eindhoven, The Netherlands. E-mail: Y.B.v.d.Burgt@tue.nl*
[d] *Center for Advanced Biomaterials for Healthcare, Istituto Italiano di Tecnologia, Largo Barsanti e Matteucci 53, Naples 80125, Italy*
[e] *Institute of Biological Information Processing – Bioelectronics, IBI-3, Forschungszentrum Jülich, Jülich, 52428, Germany. E-mail: f.santoro@fz-juelich.de*
[f] *Neuroelectronic Interfaces, RWTH Aachen, Aachen, 52074, Germany*

acquired by combining different features of memristor units. This combination improves the pattern recognition performance even with a smaller physical network size because the heterogeneous reservoir provides an extensive and diverse

Xiaodong Chen

Xiaodong Chen holds the President's Chair Professorship in Materials Science and Engineering at Nanyang Technological University (NTU), Singapore, with courtesy appointments in both chemistry and medicine. His research interests span mechanomaterials science and engineering, flexible electronics technology, sense digitalization, cyber-human interfaces and systems, and carbon-negative technology. Prof. Chen's outstanding scientific contributions have been recognized with numerous awards, including the Singapore President's Science Award, Singapore National Research Foundation (NRF) Investigatorship and NRF Fellowship, the Friedrich Wilhelm Bessel Research Award, Dan Maydan Prize in Nanoscience and Nanotechnology, Winner of Falling Walls, and Kabiller Young Investigator.

Cheol Seong Hwang

Cheol Seong Hwang received a PhD in 1993 in the Department of Inorganic Materials Science and Engineering from Seoul National University, South Korea. After finishing his postdoctoral work at the National Institute of Standards and Technology, MD USA, he joined Samsung Electronics as a senior researcher in 1994 and contributed to semiconductor memory device fields. Since 1998, he has been a professor in the Materials Science and Engineering Department at Seoul National University. He has authored or co-authored more than 714 papers in international peer-reviewed scientific journals and holds over 140 patents. His interests include semiconductor memory and logic devices, materials, and processing. He is also working actively in neuromorphic computing algorithms, devices and materials. On September 1, 2020, he was selected as the Seoul National University (SNU) Distinguished Professor.

Yoeri van de Burgt

Yoeri van de Burgt is associate professor at Eindhoven University of Technology leading the neuromorphic engineering group. He obtained his PhD in 2014 and briefly worked at a high-tech startup in Switzerland after which he worked as a postdoctoral fellow at the department of Materials Science and Engineering at Stanford University. He has been a visiting professor at the University of Cambridge in 2017 and Georgia Tech in 2022, and was awarded an ERC Starting Grant in 2018 and an ERC Consolidator Grant in 2023. Yoeri was a member of the Eindhoven Young Academy and served as the chair between 2021 - 2022. He is one of the MIT Technology Review innovators under 35 Europe 2019, TU/e Groundbreaking Researcher, Advanced Materials Rising Stars and New Scientist Talent Award nominee. Yoeri is a member of the scientific advisory board of the Centre for Cognitive Systems and Materials at the University of Groningen.

Francesca Santoro

Francesca Santoro received her Bachelor's and Master's degrees in biomedical engineering at the 'Federico II' University of Naples (Italy) with specialization in biomaterials. She received a PhD in 2014 in electrical engineering and information technology in a joint partnership between the RWTH Aachen and the Forschungszentrum Juelich (Germany). In October 2014, she joined Stanford University (USA) and received a research fellowship in 2016 from the Heart Rhythm Society. She joined IIT in July 2017 as Principal Investigator of the 'Tissue Electronics' lab. In 2018 she was awarded the MIT Technology Review Under 35 Innovator ITALIA and EUROPE. She was awarded an ERC Starting Grant in 2020. She is among the Inspiring Fifty Italy and Europe and is also the winner of the Falling Walls Science Breakthrough of the Year in Engineering and Technology in 2021. Since January 2022, she has been a professor in neuroelectronic interfaces at RWTH Aachen and Forschungszentrum Juelich. She has been recently selected as a PI in the Interstellar Initiative by the New York Academy of Science and is the recipient of the prestigious Early Career Award by the German National Academy of Science Leopoldina.

set of feature extractors. The proposed approach enhances the capacity of image recognition and time series prediction in ultra-low power edge computing devices.

These are just a few examples of the many exciting papers in this themed collection published by *Materials Horizons* and *Nanoscale Horizons* on memristors and neuromorphic systems. We hope that all readers find them an exciting read.

Finally, we would like to thank all contributing authors and reviewers of this themed collection, as well as the Editorial staff at the Royal Society of Chemistry, whose assistance was invaluable in achieving the goal of this themed collection.

References

1 C. Mead, *Nat. Electron.*, 2020, **3**, 434–435.
2 L. O. Chua, *IEEE Trans. Circuit Theory*, 1971, **CT-18**, 507–519.
3 M. K. Song, J. H. Kang, X. Zhang, W. Ji, A. Ascoli, I. Messaris, A. S. Demirkol, B. Dong, S. Aggarwal, W. Wan, S. M. Hong, S. G. Cardwell, I. Boybat, J. S. Seo, J. S. Lee, M. Lanza, H. Yeon, M. Onen, J. Li, B. Yildiz, J. A. Del Alamo, S. Kim, S. Choi, G. Milano, C. Ricciardi, L. Alff, Y. Chai, Z. Wang, H. Bhaskaran, M. C. Hersam, D. Strukov, H. P. Wong, I. Valov, B. Gao, H. Wu, R. Tetzlaff, A. Sebastian, W. Lu, L. Chua, J. J. Yang and J. Kim, *ACS Nano*, 2023, **17**, 11994–12039.
4 F. Aguirre, A. Sebastian, M. Le Gallo, W. Song, T. Wang, J. J. Yang, W. Lu, M. F. Chang, D. Ielmini, Y. Yang, A. Mehonic, A. Kenyon, M. A. Villena, J. B. Roldan, Y. Wu, H. H. Hsu, N. Raghavan, J. Sune, E. Miranda, A. Eltawil, G. Setti, K. Smagulova, K. N. Salama, O. Krestinskaya, X. Yan, K. W. Ang, S. Jain, S. Li, O. Alharbi, S. Pazos and M. Lanza, *Nat. Commun.*, 2024, **15**, 1974.
5 B. Sun, Y. Chen, G. Zhou, Z. Cao, C. Yang, J. Du, X. Chen and J. Shao, *ACS Nano*, 2024, **18**, 14–27.
6 K. He, Y. Liu, J. Yu, X. Guo, M. Wang, L. Zhang, C. Wan, T. Wang, C. Zhou and X. Chen, *ACS Nano*, 2022, **16**, 9691–9700.