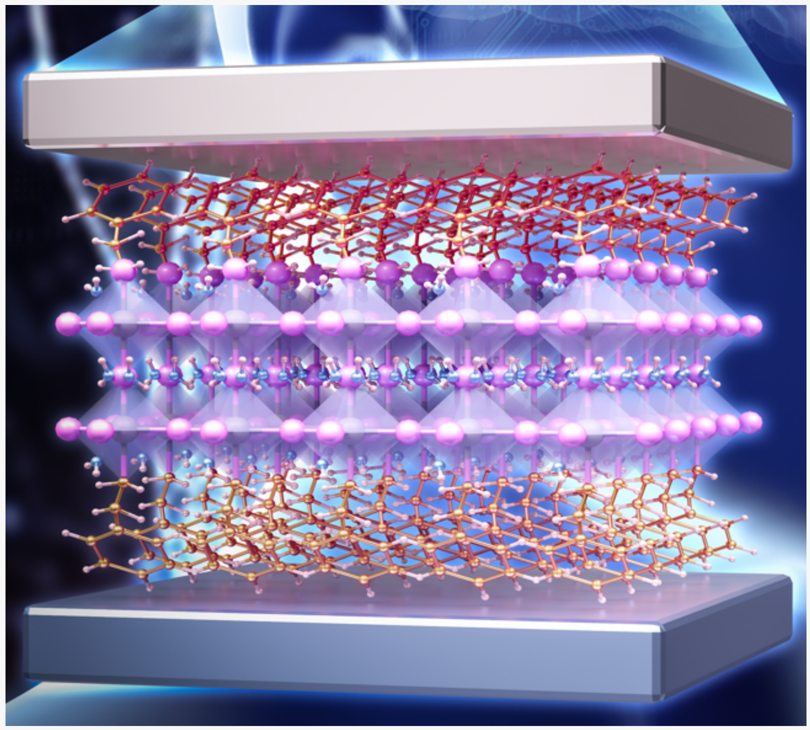
Emerging low-dimensional perovskite resistive switching memristors: from fundamentals to devices

This review provides a comprehensive picture of how low-dimensional perovskite materials could revolutionize memory devices and computing.


Device structure of a perovskite memristor

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The big-data era is witnessing significantly increased demand for smarter and more energy-efficient opto-electronic devices, which is driven by advances in artificial intelligence (AI), 5G network, and Internet of Things (IoT). The key challenge of these related technologies is processing data-intensive tasks in a quick and efficient way. Unfortunately, the traditional Von Neumann architecture in modern electronics is reaching its limits in both speed and power consumption, arising from a physically separated central processing unit and data storage units, leading to two serious problems, including “power wall” and “memory wall”. This calls for a radical departure from the traditional systems and searching for new types of memory and processing devices with non-von Neumann computational architectures. One promising solution is the in-memory computing system that emulates the functions of human brain called neuromorphic computing. Memristors have distinct advantages of small size, fast processing speed, low energy consumption, by combining memory and computation within the same units. These features make them attractive for future electronics.

This review article focuses on a special group of materials called low-dimensional perovskite semiconductors, which are being explored as the active layers inside memristors, with varying degrees of success. Perovskites are a class of materials with unique optical and electrical properties such as tunable bandgap, high absorption coefficient, long carrier diffusion length, which are widely used in optoelectronics, including solar cells, light-emitting diodes, transistors, and others. Particularly, the low-dimensional structure with structural diversity by incorporating bulky organic spacer cations makes them more stable for memory device applications. This report summarizes the latest advances in developing low-dimensional perovskite memristors. The crystal structure and ion migration, which can change the electrical resistance of the device, a key feature for memory applications, are explained. The working mechanism of perovskite memristors and the corresponding electrical parameters of the devices are discussed. Dimensionality of perovskite materials has a significant impact on the performance of memristors. This review also explores the correlation between structure variation of perovskite and performance of memory devices.

Another important part of the article is the discussion of how the electrical parameters of switching current ratio, threshold voltage, retention time, cycling endurance and/or multi‐resistance states devices can be improved. The authors review several strategies that can make memristors more reliable and operationally stable for practical applications. These strategies, such as adjusting the composition of the perovskite semiconductors, designing better contact interfaces between different functional layers in the device, and employing different electrode materials. Finally, the review highlights the major challenges that still need to be solved before low-dimensional perovskite memristors can be widely used in real-world technologies. These issues include material stability, large-scale manufacturing, and integration with existing electronic systems. Despite these limitations, the authors are confident that the research field will grow more rapidly soon and many new opportunities will emerge. They believe that with continued research in the community, low-dimensional perovskite memristors have the potential to play a key role in modern electronics, enabling smarter, faster, and more energy-efficient devices and systems.

In summary, this review provides a comprehensive picture of how low-dimensional perovskite materials could revolutionize memory devices and computing, which is expected to inspire new ideas and discussions in the near future.

The research group of Prof. Dr. Peter Müller-Buschbaum at the Technical University of Munich reviews recent progress on low-dimensional perovskite memristors, a cutting-edge field that combines advanced materials with novel memory devices. Perovskite semiconductors are well known for their unique materials chemistry, remarkable electrical and optical properties, and low-cost manufacturing, showing intriguing application potential for various optoelectronic devices. Driven by the understanding of physical and chemical properties of perovskites in solar cells and light-emitting diodes, these materials are now being investigated in memory technologies. This hybrid layered structure of low-dimensional perovskites with organic components provides an exciting platform for designing unprecedented materials and functionalities at the molecular level, making them highly promising for memristor applications. By providing a comprehensive and up-to-date overview of the advances in this research field, the review serves as a valuable resource for both researchers and engineers. It explains the structural diversity of low-dimensional perovskite materials, the device geometry of memristors and the corresponding working mechanisms, highlighting engineering strategies that can improve the electrical parameters of memory devices. This work is particularly timely for researchers working with next-generation computing platforms, wearable electronics and smart sensors. Beyond computing, memristors may also contribute to sustainable technology by reducing energy consumption and enabling more efficient use of electronic resources.

In the broader context of materials science, electronics, and information technology, this review highlights a transformative and interdisciplinary direction inspired by biology, physics, and chemistry. By shedding light on the advances and challenges in the field of low-dimensional perovskite memory devices, the review provides critical insights that will have a positive impact on the community and support the design of the next generation of intelligent, efficient, and adaptive electronic systems.

Prof. Dr. Peter Müller-Buschbaum is a full professor at the Technical University of Munich (TUM), Germany, where he heads the Chair of Functional Materials (E13 group) in the School of Natural Sciences. He also serves as the scientific director of the Bavarian key lab TUM.solar. Since January 2024, Prof. Müller-Buschbaum has been a Deputy Editor for the journal ACS Applied Materials & Interfaces, published by the American Chemical Society (ACS). Furthermore, he has been the supervising professor for the "Elektroniklabor" (Electronics Laboratory) at the TUM School of Natural Sciences since November 2023 and a member of the TUM Sustainability Board since May 2023. He is a former scientific director of the Munich Neutron Source FRM II and the Heinz Maier-Leibnitz Zentrum (MLZ).

The research group of Prof. Dr. Peter Müller-Buschbaum is actively involved in the Munich Institute of Integrated Materials, Energy and Process Engineering (MEP) at the Technical University of Munich. Our research interests primarily focus on polymer, perovskite, and hybrid materials for energy and sensing applications, with a special emphasis on thin films and nanostructures, including kinetic, in situ, and operando experiments. Current projects are centered on functional materials such as polymer-based inorganic-organic hybrid solar cells, organic solar cells, lithium-ion batteries, perovskite devices, and nanogenerators. The general aim of our research is to infer functional properties of condensed matter from knowledge of its microscopic dynamics and structure.

Andrew Smith
Charlesworth
+ +44 7753 374162
marketing@charlesworth-group.com
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