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Interstitial nanofilament pathway reduces energy consumption in memristors

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Molecular crystals with interstitial filaments enable memristors with zeptojoule-level switching energy and over one billion switching cycles, offering a scalable path to energy-efficient and reliable in-memory computing.

Resistive switching devices, or memristors, are key candidates for enabling non-von Neumann in-memory computing systems due to their ability to simultaneously store and process information. However, the mainstream development of memristor technologies has long been constrained by the uncontrolled, stochastic formation and rupture of thick conductive filaments, which in turn induce structural damage in conventional oxide-based materials during repeated switching. This type of filament formation results in high energy consumption and poor endurance. Now, writing in *Nature Nanotechnology*, Qin et al.[1] report a memristor based on a Sb_2O_3 molecular crystal consisting of van der Waals (vdW)-bonded molecular cages that overcomes these limitations by forming an interstitial pathway of conductive nanofilaments, achieving ultralow energy consumption (~26 zJ) and endurance exceeding 10^9 cycles.

Traditional memristors are typically built from oxides, such as HfO_2 or TaO_x, and two-dimensional materials, such as hexagonal boron nitride (hBN) or MoS_2, where resistive switching relies on ion migration through defect sites or grain boundaries[2–6] (Fig. 1a). In this

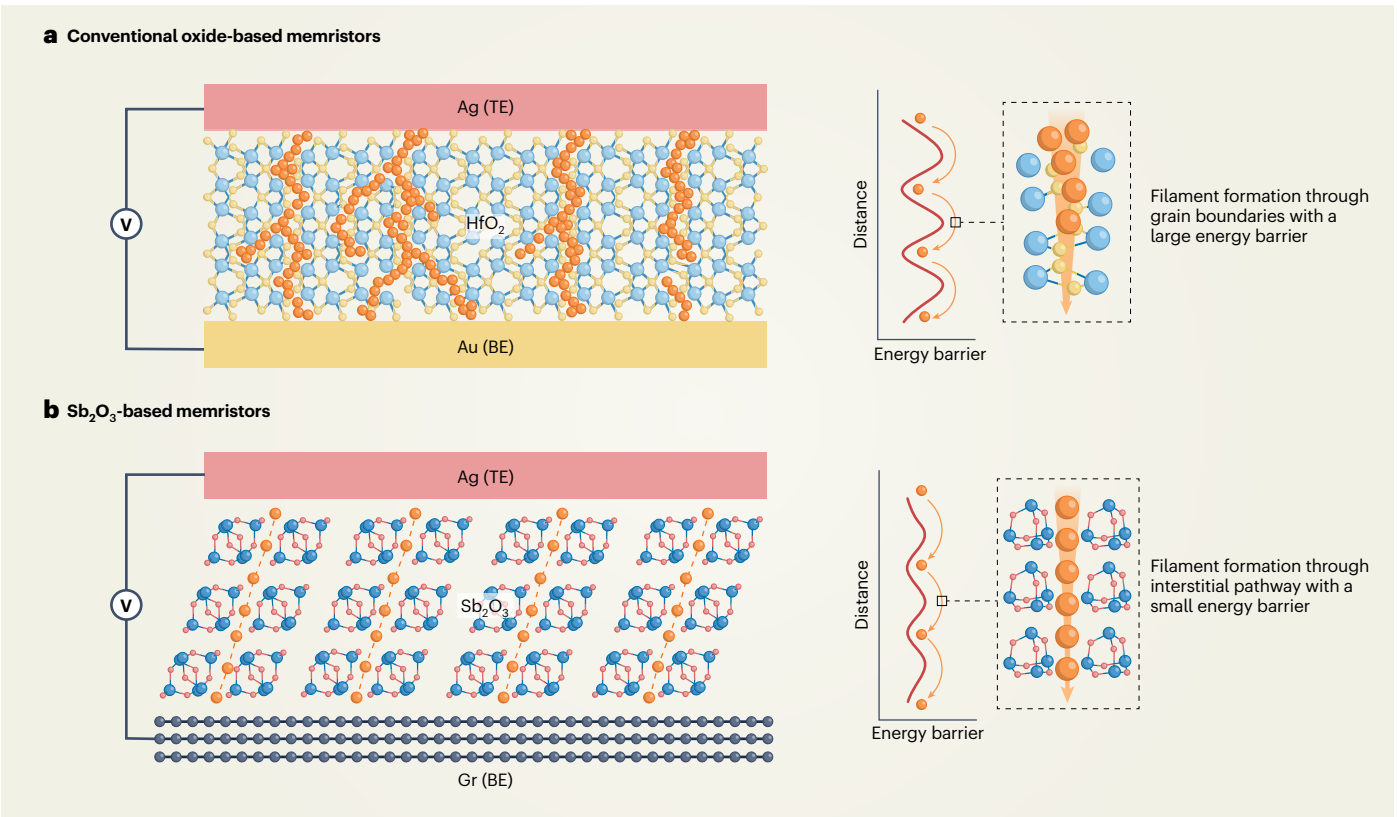

Fig. 1 | Comparison of conductive filament formation in conventional oxide memristors and molecular crystal memristors. a, In conventional oxide memristors, Ag ions migrate through randomly distributed grain boundaries in HfO_2, overcoming high energy barriers. This process often results in irreversible lattice distortion and high energy consumption. **b**, In contrast, molecular crystal memristors possess inherent interstitial sites that facilitate Ag ion migration with minimal structural disruption, leading to ultra-low energy consumption and superior cyclic endurance. TE, top electrode; BE, bottom electrode; Gr, graphene. Figure adapted from ref. 9, ACS.

traditional switching mechanism, excessive energy consumption is required to overcome high energy barriers associated with ion migration. Furthermore, the resulting conductive filaments are often thick and random, thus leading to cumulative lattice damage, ultimately degrading device performance. In contrast, molecular crystals offer a fundamentally different platform. In Sb_2O_3, discrete Sb_4O_6 cages are loosely connected via vdW interactions, creating inherent and uniform interstitial spaces[7–9]. As a result, ion migration can occur by overcoming only the low energy barriers consisting of these weak vdW forces, enabling low-energy operation in the molecular crystal memristors (Fig. 1b). Moreover, the resulting conductive nanofilaments are thin and uniform, thus preserving structural integrity — unlike in traditional memristive channel materials.

The device architecture developed by Qin et al. consists of a 10-nm-thick Sb_2O_3 film sandwiched between an Ag top electrode and an inert bottom electrode (either few-layer graphene or Au), forming a typical crossbar array. This structure enables stable bipolar resistive switching with high on/off ratios (>10^5) by tuning the compliance current. This well-established reconfigurable behaviour is highly desirable for a variety of neuromorphic applications, such as convolutional neural network and reservoir computing (RC) systems. Furthermore, the energy consumption was estimated for the set process at a minimal compliance current, showcasing considerably low values compared to previous reported oxide or two-dimensional material-based memristors. In the convolutional image processing with a 5 x 5 crossbar array, low energy consumption for an average single convolution computation was also implemented. In addition, the design's effectiveness was confirmed down to the nanoscale (~8 nm), where the devices maintained robust switching behaviour and consistent electrical properties. These ultra-small devices retained their reconfigurable switching behaviour and exhibited consistent electrical characteristics, affirming the robustness of the filament formation mechanism in Sb_2O_3 at extremely small footprints.

To verify the underlying mechanism of filament formation in the molecular crystals, Qin et al. combined computational methods with high-resolution experimental imaging. Density functional theory simulation revealed that the energy barrier for Ag ion migration in Sb_2O_3 molecular crystals is significantly lower than in conventional materials, such as HfO_2, hBN, and MoS_2. Further modelling of structural evolution showed that Ag ions first occupy twisted hexagonal interstitial sites and then octahedral sites within the vdW gaps, to form one-dimensional atomic chain filaments that serve as conductive paths as the Ag content increases. With the aid of in situ transmission electron microscope, Qin et al. experimentally confirmed the proposed structural evolution model. During the switching, changes in the lattice parameters of Sb_2O_3 were highly reversible with Ag ion insertion and extraction while preserving the molecular cage architecture, showcasing the negligible structural damage and explaining the remarkable endurance of the molecular crystal memristors, in contrast with the filamentary damage observed in traditional devices.

Pushing the concept toward practical applications, 1024 × 1024 crossbar arrays on 8-inch complementary metal–oxide–semiconductor-compatible wafers were fabricated with a one-transistor-one-resistor configuration. Due to the reconfigurable switching behaviour of the molecular crystal memristors, Qin et al. implemented both RC and current readout for artificial neural networks on a single chip. This integrated approach offers a clear advantage over conventional RC systems, which requires two distinct types of memristors for reservoir and readout layers. Impressively, the system achieved 100% accuracy in sequential image recognition tasks, underscoring its functional capability.

The work by Qin et al. introduces a new class of memristor materials that leverage inherent interstitial pathways formed by weak intermolecular interactions. These results illustrate not only the energy and endurance advantages of the molecular crystal memristor, but also its viability for real-world computing applications. However, several challenges remain. Memristors have historically suffered from issues, such as non-linearity and high stochasticity, while programming. Addressing these limitations will require continued research and material innovation, although the conductive nanofilaments in molecular crystal memristors appears promising in terms of low energy consumption and high cyclic endurance. Furthermore, the low formation energy of these nanofilaments — even though beneficial for energy efficiency — may indicate that rupture can occur easily as well, compromising their long-term retention. As such, further investigation into the retention characteristics of molecular crystal memristors under various conductance states is necessary. In addition, the stability of Sb_2O_3 under ambient or integrated system conditions remains an open question. The use of active metals like Ag in crossbar configurations also warrants scrutiny, particularly regarding potential crosstalk and diffusion effects. Finally, while CMOS integration is demonstrated, compatibility with backend-of-line processing temperatures and processes will be essential for commercial deployment.

Nonetheless, this work provides a substantial advance in the development of energy-efficient, reliable and scalable memristors. By leveraging the unique structural features of molecular crystals, the authors pave a promising path towards post-von Neumann computing architectures.

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Competing interests

The authors declare no competing interests.