Editorial

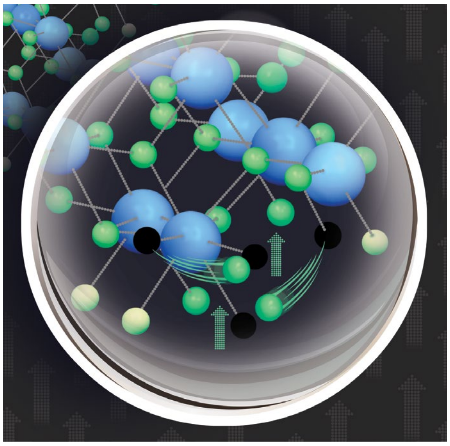
https://doi.org/10.1038/s41563-023-01557-6

Ferroelectrics forge forward

Ferroelectrics have already impacted scientific research and commercial applications, but they still show plenty of potential to surprise.

The study of ferroelectrics is now more than a century old. These materials typically, upon undergoing a phase transition as the temperature decreases below a critical value, possess a permanent and hysteretic electrically switchable polarization. As a result, ferroelectrics have already had an impact on diverse applications ranging from actuators, to electronic memories[1]. Moreover, following advances in characterization techniques, combined with the ongoing evolution of computational modelling, insight into the fundamental mechanisms that drive these materials has continued to progress, in turn enabling improved properties for applications. In this focus issue, we feature three Perspective articles and a Picture Story that discuss some of the new directions that the study and application of ferroelectrics are heading towards.

The ground state of a ferroelectric is polar, implying that a prerequisite for designing new ferroelectrics should be to start from stable materials that have polar structures and so permanent polarization. However, following the synthesis of 10-nm-thick films of hafnium dioxide (or hafnia), ferroelectricity was observed in a material that in the bulk is non-polar[2]. This showed that at the nanoscale it is possible to generate ferroelectricity in metastable materials. The observation of ferroelectricity in hafnia, silicon-compatible and the high-*k* dielectric material of choice for current semiconductor technologies, sparked considerable research and industrial interest. In a Perspective article by Beatriz Noheda and colleagues, the lessons learned from hafnia are examined. Beyond the commonly discussed applications of hafnia ferroelectrics in field-effect transistors and random-access memories, electromechanical applications such as piezoelectric energy harvesting are discussed, and it is noted that destabilization of the ferroelectric phase could enhance the piezoelectric response. An overview of the ferroelectric mechanism is provided, which is known to not follow the same process as other ferroelectrics. Oxygen migration and surface electrochemical effects are noted to be present and influence ferroelectricity, while it is hypothesized that the polar phase of hafnia could be an adaptive phase. And strategies for making other binary oxides polar are considered, expanding the space for inorganic ferroelectrics beyond the perovskites.



In this issue, we put ferroelectrics under the microscope.

CREDIT: CONCEPT, BEATRIZ NOHEDA, PAVAN NUKALA AND MÓNICA ACUAUTLA; ARTIST, TANUJA GOYAL

Hafnia is an example of a ferroelectric that only forms when a thin film is grown, but ferroelectricity has also been observed in even thinner, monolayer and few-layer two-dimensional (2D) van der Waals (vdW) materials. In a Perspective article by Junling Wang and colleagues, research on and the challenges of 2D vdW ferroelectrics are discussed. The mechanisms that generate ferroelectricity in vdW materials are surveyed; these can range from the ionic displacement (see image) or ordering of polar groups that generate ferroelectricity, to more exotic cases such as interlayer sliding between two or more vdW layers[3] or twisted moire bilayers[4] that cause charge redistribution and so generate ferroelectricity. The reduced dimensionality of these systems can lead to unique properties. Polar thermal stability can be enhanced, and ferroelectricity and metallicity can coexist. The opportunities for using these materials in applications are discussed, such as stacking 2D ferroelectric and magnetic materials to make a multiferroic or designing non-volatile polarization-controlled spin devices, while challenges that need to be met, such as greater investigations of polarization-switching mechanisms and kinetics, or scaling the growth of these materials, are outlined. A Picture Story in this issue also covers vdW ferroelectrics, discussing a *Nature* paper on the generation of multiple polarization states by sliding of individual layers in multilayer WSe_2 and MoS_2, indicating that it is possible to design vdW ferroelectrics with multiple polarization states[5].

This is not to say that research in classical perovskite ferroelectrics has not also seen exciting developments. There is a growing realization that the complex topological patterns of polarization that form in ferroelectrics with multiple polarization domains can present surprising properties. In a Perspective article by Nagarajan Valanoor and colleagues, the structure, origin and applications of a class of topological ferroelectric structures known as the spherical ferroelectric solitons are discussed. These typically require a very delicate balance of boundary conditions to form, as found in ultrathin films, nanodots or superlattices. The manipulation of these structures under an electrical field or mechanical deformation is surveyed, and prospects for the study and application of these systems are considered. New functionalities have been seen with these phenomena, for example negative capacitance, while ultrafast tuning upon laser irradiation could enable rapid and large tunability of dielectric permittivity. Similar nanoscale spherical domains have also been seen in magnetic materials, and it would be interesting to investigate in multiferroic materials if both ferroelectric and magnetic spherical solitons could coexist, and if they could be separately manipulated.

The study of ferroelectrics has been a fruitful field, for both fundamental and applications studies. With further detailed study, and with better materials synthesis, characterization and modelling tools, this seems as if it will continue to be the case.

References

1. Trolier-McKinstry, S. *Am. Ceram. Soc. Bull.* **99**, 22–23 (2020).
2. Böscke, T. S., Müller, J., Bräuhaus, D., Schröder, U. & Böttger, U. *Appl. Phys. Lett.* **99**, 102903 (2011).
3. Fei, Z. et al. *Nature* **560**, 336–339 (2018).
4. Zheng, Z. et al. *Nature* **588**, 71–76 (2020).
5. Deb, S. et al. *Nature* **612**, 465–469 (2022).