enhancing clearance at the blood–brain barrier can improve lymphatic drainage function. ■

Melanie D. Sweeney *and* **Berislav V. Zlokovic** *are in the Department of Physiology and Neuroscience and at the Zilkha Neurogenetic Institute, Keck School of Medicine, University of Southern California, Los Angeles, California 90089–2821, USA.*

e-mail: zlokovic@usc.edu

1. Alitalo, K., Tammela, T. & Petrova, T. V. *Nature* **438**, 946–953 (2005).
2. Mascagni, P. *Vasorum lymphaticorum corporis humani historia et ichnographia* (Pazzini Carli, 1787).
3. Aspelund, A. *et al. J. Exp. Med.* **212**, 991–999 (2015).
4. Louveau, A. *et al. Nature* **523**, 337–341 (2015).
5. Absinta, M. *et al. eLife* **6**, e29738 (2017).
6. Da Mesquita, S. *et al. Nature* **560**, 185–191 (2018).
7. Sweeney, M. D., Sagare, A. P. & Zlokovic, B. V. *Nature Rev. Neurol.* **14**, 133–150 (2018).
8. Zhao, Z. *et al. Nature Neurosci.* **18**, 978–987 (2015).
9. Xie, L. *et al. Science* **342**, 373–377 (2013).
10. Courtice, F. C. & Simmonds, W. J. *Aust. J. Exp. Biol. Med. Sci.* **29**, 255–263 (1951).
11. Shibata, M. *et al. J. Clin. Invest.* **106**, 1489–1499 (2000).
12. Deane, R. *et al. Neuron* **43**, 333–344 (2004).

This article was published online on 25 July 2018.

CONDENSED-MATTER PHYSICS

Stable and switchable polarization in 2D

The electric polarization of materials called ferroelectrics is often suppressed by an internal electric field, limiting uses for these materials. The discovery of a thin-film ferroelectric that is resistant to this field represents a major advance.

TURAN BIROL

Materials known as ferroelectrics have a macroscopic, switchable electric polarization that can be controlled by an external electric field[1]. This strong coupling to electric fields, however, is also the bane of ferroelectrics. Electric charges that accumulate on the surfaces of these materials produce an internal electric field called a depolarization field that, if not mitigated by external electrodes, is often large enough to suppress the polarization completely. Writing in *Physical Review Letters*, Xiao *et al.*[2] report the observation of ferroelectricity that is invulnerable to the depolarization field in thin films of indium selenide (In_2Se_3). This feature results from an atypical mechanism that drives the ferroelectricity in indium selenide, and opens the way for both the discovery of other ferroelectrics and further applications for them.

Ferroelectric polarization originates from an asymmetric distribution of atoms in a material's crystal structure — positively charged ions and negatively charged ions are slightly shifted from a symmetric distribution, in opposite directions[3] (Fig. 1). However, this arrangement of atoms produces charges on the material's surface, and these charges generate a depolarization field that opposes the polarization. In thin-film ferroelectrics, if the polarization is perpendicular to the plane of the film — the preferable direction for applications — the depolarization field is usually strong enough to suppress the polarization completely. This suppression limits the potential uses of ferroelectrics in, for example, computer memories[4] and semiconductor-based electronic devices[5].

The most commonly studied ferroelectrics are perovskite oxides such as barium titanate ($BaTiO_3$). In this archetypal ferroelectric, the driving force behind the polarization is the long-range electrostatic (Coulomb) interaction between atoms. Covalent bonds, which involve the sharing of electron pairs between atoms, play a smaller part than the Coulomb interaction in determining the material's ferroelectricity[6].

Xiao and colleagues instead studied indium selenide, which is a chalcogenide — a compound based on one of the elements in the same group of the periodic table as oxygen. Going down this group, from oxygen to sulfur to selenium, an atom's tendency to attract electrons in a chemical bond towards itself decreases. As a result, bonds have a more strongly covalent character in sulfides and selenides than in oxides, and have a larger effect on the compound's properties.

Indium selenide is a two-dimensional material that consists of five alternating indium and selenium layers, in which the indium–selenium bonds are strongly covalent. Previous theoretical work showed that there are many long-lived atomic configurations of indium selenide that differ in the local bonding environment of the ions in the material's central layers[7]. This work also predicted that the ferroelectric polarization in indium selenide is driven by local covalent bonds, rather than by long-range interactions, and that these bonds are strong enough to prevent the depolarization field from suppressing the polarization — even in thin films that are 3 nanometres thick (equivalent to about three sheets of indium selenide), like those of Xiao and colleagues.

Xiao *et al.* synthesized their films using both exfoliation (the removal of sheets from a bulk material) and a technique known as van der Waals epitaxial growth, which is an ideal method for growing materials that, like indium selenide, have weakly bound layers[8]. Using imaging tools such as piezoresponse force microscopy, the authors observed a polarization perpendicular to the plane of the film that is stable at temperatures of up to 700 kelvin. They also detected switching of this polarization at room temperature when an electric field was applied.

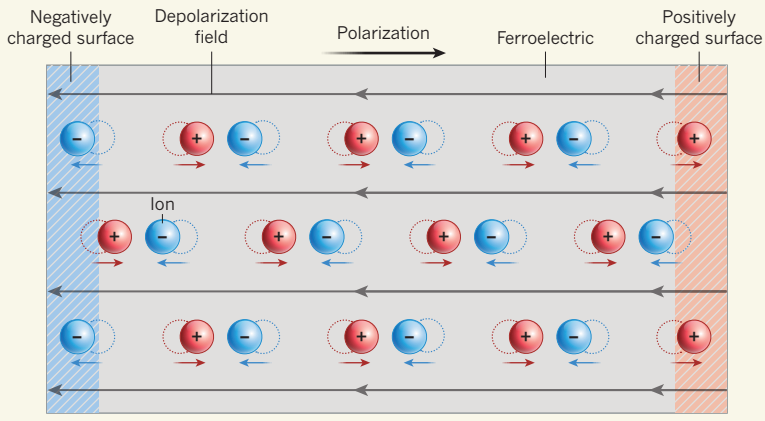

Figure 1 | Ferroelectric polarization. The electric polarization of materials called ferroelectrics originates from the fact that positively charged ions and negatively charged ions are slightly shifted from a symmetric distribution (dotted circles) in opposite directions (coloured arrows). The surfaces of ferroelectrics are negatively or positively charged owing to the presence of unpaired ions. Such charges produce an electric field known as a depolarization field that usually suppresses the polarization, limiting applications for these materials. Xiao *et al.*[2] report a ferroelectric in which covalent bonds (not shown) between ions are sufficiently strong that the depolarization field cannot suppress the polarization.

This is not the first report of ferroelectricity in a thin film of a chalcogenide. It is, however, the first observation of an out-of-plane polarization in an atomically thin chalcogenide film that is stable without electrodes mitigating the depolarization field. Such a feature, along with the stability of the polarization at high temperatures, makes indium selenide promising for applications. Now that a chalcogenide has been discovered that has persistent out-of-plane polarization, and in which the mechanism of ferroelectricity is known, we will definitely hear more about chalcogenide ferroelectrics in the coming years.

One previously known group of ferroelectrics that are impervious to the depolarization field are the 'improper' ferroelectrics. In these materials, the emergence of the polarization can be considered to be a side effect of some other structural transition[1]. However, rather than being an improper ferroelectric, indium selenide is more likely to be a member of a special group of proper ferroelectrics: the hyperferroelectrics. Such materials have been studied in detail using theoretical approaches[9], but their polarization has not yet been experimentally shown to be switchable.

Hyperferroelectricity was originally predicted to exist in a group of compounds containing three different elements that, like indium selenide, have a polarization driven by covalent bonds[9]. In these compounds, the Born effective charges (the changes in polarization with respect to the amount by which atoms are displaced) are smaller than those in typical oxide ferroelectrics. As a result, hyperferroelectrics are more resistant to the depolarization field than are their oxide counterparts. So far, indium selenide has not been confirmed as a hyperferroelectric. But if indium selenide were found to be the first hyperferroelectric that contains only two elements, this could lead to the discovery of other 2D chalcogenide ferroelectrics.

Xiao and colleagues' study shows that 2D chalcogenides must be taken seriously in the search for ferroelectrics for technological applications. But it also emphasizes how little is known about the ferroelectricity in this family of materials, compared with the perovskite oxides. The authors' results should also be considered in the context of the increasing interest in the electronic properties of 2D chalcogenides, which can involve exotic phenomena such as quantum spin Hall physics and Weyl semimetals. Future work will surely study the coupling between these phenomena and the polarization, because it could enable different electronic phases to be controlled using electric fields. ■

Turan Birol *is in the Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455, USA.*
e-mail: tbirol@umn.edu

1. Lines, M. E. & Glass, A. M. *Principles and Applications of Ferroelectrics and Related Materials* (Oxford Univ. Press, 2001).
2. Xiao, J. *et al. Phys. Rev. Lett.* **120**, 227601 (2018).
3. Rabe, K., Ahn, C. H. & Triscone, J.-M. (eds) *Physics of Ferroelectrics: A Modern Perspective* 1–30 (Springer, 2007).
4. Takashima, D. & Kunishima, I. *IEEE J. Solid State Circuits* **33**, 787–792 (1998).
5. Hoffman, J. *et al. Adv. Mater.* **22**, 2957–2961 (2010).
6. Cohen, R. E. & Krakauer, H. *Phys. Rev. B* **42**, 6416–6423 (1990).
7. Ding, W. *et al. Nature Commun.* **8**, 14956 (2017).
8. Walsh, L. A. & Hinkle, C. L. *Appl. Mater. Today* **9**, 504–515 (2017).
9. Garrity, K. F., Rabe, K. M. & Vanderbilt, D. *Phys. Rev. Lett.* **112**, 127601 (2014).

This article was published online on 30 July 2018.

MATERIALS SCIENCE

Designer topology in graphene nanoribbons

In materials known as graphene nanoribbons, topological states can be precisely engineered and probed, providing an experimental platform for studying electronic topology. SEE LETTERS P.204 & P.209

KATHARINA J. FRANKE & FELIX VON OPPEN

For more than a decade, two-dimensional sheets of carbon atoms known as graphene have captured researchers' imaginations. Last year, it was predicted that electronic states in narrow strips of graphene — dubbed graphene nanoribbons — could have different topologies depending on the width of the strip[1]. On pages 204 and 209, respectively, Rizzo *et al.*[2] and Gröning *et al.*[3] report experiments that confirm this prediction. Their results show that graphene nanoribbons provide a flexible and highly precise platform for designing and fabricating materials that have what is known as a non-trivial topology. The authors suggest that such materials could be used to realize desired exotic topological states for quantum technologies.

We learn in school that materials can differ starkly in their electrical properties. The difference between conductors and insulators is rooted in the states that are available to the electrons in these materials. In conductors, such as metals, electrons can move freely because available states exist at arbitrarily low energies. By contrast, the electrons in insulators are effectively localized, and do not conduct electricity unless they are provided with sufficient energy to overcome an energy gap.

This understanding of conductors and insulators was an early triumph for the application of quantum theory to materials. However,

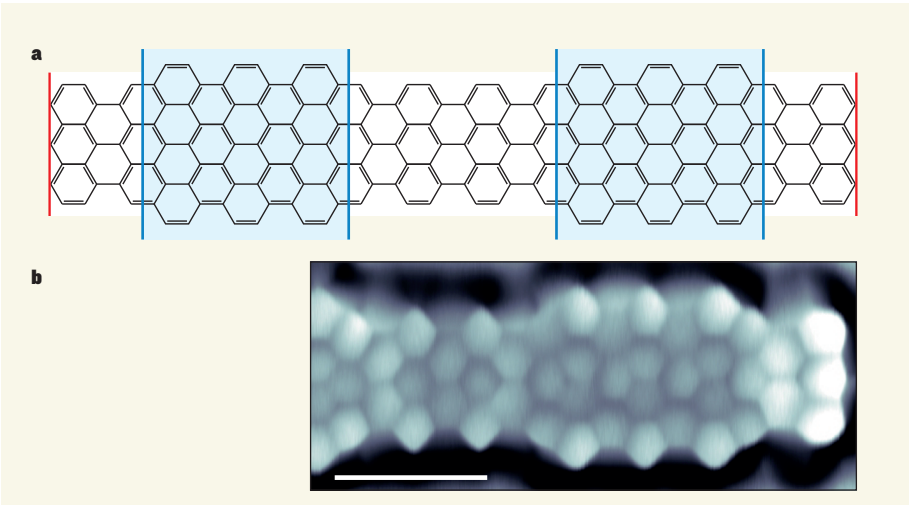

IMAGE: D. J. RIZZO *ET AL.*/*NATURE*

Figure 1 | A graphene nanoribbon. **a**, Rizzo *et al.*[2] and Gröning *et al.*[3] synthesized strips of graphene (a two-dimensional form of carbon) known as graphene nanoribbons (black). The nanoribbons alternated in width such that the topologies of electronic states in the narrow sections (white) and wide sections (blue) were trivial and non-trivial, respectively. The authors report localized topological electronic states at the junctions (blue lines) between narrow and wide sections, and at the ends (red lines) of the nanoribbons. **b**, This micrograph shows one end of a nanoribbon studied by Rizzo and colleagues. Scale bar, 1 nanometre.