in the rift zone might have been vapour at shallow depths[12], and at greater depths it could have been a supercritical fluid (a substance that is not in a distinct liquid or gas phase, but has properties of both). The high compressibility of both vapours and supercritical fluids would dampen the magnitude of pressure changes in the authors' model, making failure less probable.

How, then, can we test the hypothesis that rainfall initiated the lower east rift zone eruption? Unfortunately, subsurface pressure measurements – and hydrogeological data more generally – are rarely part of volcano monitoring. Instead, as with many geoscience and Earth-history questions, we have to look back in time using the geological and historical record of eruptions. In support of their hypothesis, Farquharson and Amelung analysed all reported eruptions at Kīlauea since 1790, and showed that the volcano tends to erupt at the wettest time of year.

Should we increase alert levels at volcanoes after heavy rainfall? We could ask the same question about other stress changes, such as those from regional earthquakes. This is an open question. These stress changes are small, and hence, if anything, modulate the exact timing of the surface eruption. At Kīlauea, there were other sources of stress – in fact, a change in eruption behaviour had been anticipated on the basis of ground-deformation measurements and inferred magma movement. The Hawaiian Volcano Observatory issued a warning on 17 April that a new vent might open[1].

The possibility that external processes initiate volcanic eruptions is a reminder that volcanoes are part of a dynamic Earth system. Volcanic eruptions influence all surface environments, including climate and weather[13]. Changes in those surface environments, such as heavy rainfall, might also influence eruptions. We are only just beginning to understand these interactions.

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1. Neal, C. A. *et al. Science* **363**, 367–374 (2019).
2. Farquharson, J. I. & Amelung, F. *Nature* **580**, 491–495 (2020).
3. Montgomery-Brown, E. K., Shelly, D. R. & Hsieh, P. A. *Geophys. Res. Lett.* **46**, 3698–3705 (2019).
4. Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R. & Davies, R. J. *Earth Sci. Rev.* **178**, 438–514 (2018).
5. Keranen, K. M., Weingarten, M., Abers, G. A., Bekins, B. A. & Ge, S. *Science* **345**, 448–451 (2014).
6. Jellinek, A. M., Manga, M. & Saar, M. O. *J. Geophys. Res. Solid Earth* **109**, B09206 (2004).
7. Boulahanis, B. *et al. Earth Planet. Sci. Lett.* **535**, 116121 (2020).
8. Linde, A. T. & Sacks, I. S. *Nature* **395**, 888–890 (1998).
9. Avouris, D. M., Carn, S. A. & Waite, G. P. *Geology* **45**, 715–718 (2017).
10. Gudmundsson, A. *Volcanotectonics: Understanding the Structure, Deformation and Dynamics of Volcanoes* (Cambridge Univ. Press, in the press).
11. Gansecki, C. *et al. Science* **366**, eaaz0147 (2019).
12. Hsieh, P. A. & Ingebritsen, S. E. *J. Geophys. Res. Solid Earth* **124**, 1498–1506 (2019).
13. National Academies of Sciences, Engineering, and Medicine. *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing* (National Academies, 2017).

Condensed-matter physics

Permanent electric control of spin current

Stefano Gariglio

The development of low-power methods for controlling a property of electrons known as spin could help to maintain the historic rates of progress that are occurring in computational power. Just such a method has now been reported. **See p.483**

A promising technology for the next generation of computers is spintronics, a type of electronics that depends on the spin – the intrinsic angular momentum – of electrons, rather than their charge. However, available methods for controlling spin require electric currents that are too large for practical applications. On page 483, Noël *et al.*[1] report an approach that allows low-power spin control using an electric field.

The exponential progress in increasing computational power over the past 50 years has been largely driven by the relentless miniaturization of the field-effect transistor[2], the basic component of silicon chips. This consistent downscaling was anticipated[3] in 1965 by electronic engineer Gordon Moore, and has led to the staggering 2 billion transistors that are now typically found in the processors of modern personal computers. The semiconductor industry has come up with a road map outlining the technological developments in computer materials, devices and systems that will be needed to maintain these historic rates of increase in computational power (https://irds.ieee.org).

A growing section of the road map addresses a pressing problem for the field: transistors based on currently used technology cannot be scaled down much further, because the physical limits of miniaturization will soon be reached. There are no known solutions for several of the technical and materials issues associated with this problem. Materials scientists, physicists and engineers are therefore investigating an array of potential new working principles for computer technology. The development of new approaches also allows other goals to be targeted, such as lowering energy consumption, or incorporating multiple functionalities into components to speed up data processing.

One way of reducing power consumption would be to eliminate the need for a continuous power supply to maintain the logic state (ON or OFF) of transistors. This can be achieved using ferroic materials (such as ferroelectric compounds, which have a permanent electric polarization) or piezoelectric mechanical devices, which require power to switch between the logic states, but not to retain those states[4]. Spintronics technology has also seen a surge of interest, because this approach is expected to reduce electrical dissipation[5] – wasteful loss of electrical power as heat. Combinations of ferroic approaches with spintronics[6] could be particularly effective in the race to develop more-efficient computing technology.

However, many of these approaches will require new materials – for example, the semiconductors used in conventional electronic devices do not have ferroic properties. A family of compounds known as complex oxides are of particular interest, because they host permanent electric and magnetic dipoles, thereby opening the door to applications that require permanent states. Although complex oxides are not as good as semiconductors for use in classical transistors because they produce more electrical dissipation, they have remarkable properties for spintronics[7].

Interesting electronic phases have been observed to form at the interfaces between two complex oxides. Noël and co-workers focus on a phase called an electron gas: an ultrathin (a few nanometres thick) layer of conducting electrons that forms at the surface of strontium titanate (STO) that has been covered by a layer of aluminium.

STO probably provides the best illustration of the complexity of the electrical properties of transition-metal oxides. In its pure form, it is a dielectric material (an electrical insulator) that has a tendency to become ferroelectric at temperatures below 4 kelvin, but fails to do so

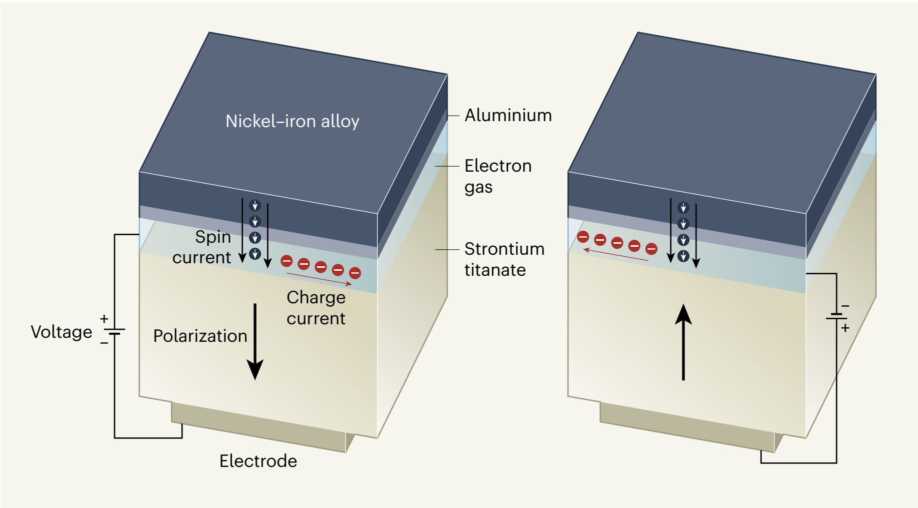

Figure 1 | A 'ferroelectric-like' spin–orbit transistor. A type of electronics known as spintronics involves controlling the spin (the intrinsic angular momentum) of electrons. Noël *et al.*[1] injected a spin current (arrows in circles indicate electron spins) from a magnetic nickel–iron alloy into strontium titanate (STO). The STO was covered by a thin layer of aluminium, which induces the formation of an electron gas (a layer of highly mobile electrons) at the STO surface. The electrons in the gas exhibit spin–orbit coupling – their spins couple to their momenta. This effect converts the spin current into a conventional charge current (red circles indicate electron charges). The authors applied a voltage across the insulating STO beneath the electron gas to change the sign of the spin–orbit coupling, and hence the direction of the charge current. The insulating STO exhibits surprising 'ferroelectric-like' behaviour: it has an overall electrical polarization whose direction (large arrow) depends on the applied voltage. The polarization remains in the absence of an electric field; this allows permanent control of the spin–orbit coupling and thereby of the direction of the charge current.

because of quantum fluctuations[8]. However, tweaks to the chemistry of STO (such as the replacement of some of the strontium atoms by calcium atoms) can push the compound over the edge to become truly ferroelectric[9]. And the replacement of some of the strontium atoms by lanthanum atoms increases the number of electrons in STO through a process known as electron doping, and turns the material into a metallic conductor, and even into a superconductor[10].

One consequence of the electrons at the aluminium/STO interface becoming confined in a gas is that their spin is coupled to their momentum, a phenomenon called spin–orbit interaction[11]. Workers from the same research group as Noël *et al.* have previously demonstrated[12] such spin–momentum entanglement: when they injected a spin-polarized current (a flow of spins that are oriented in one direction) into the electron gas, they observed a conventional electric current (a charge current) whose direction depends on the spin orientation and on the spin–orbit coupling. This is the result of the spin polarization being converted into electron motion by the spin–orbit interaction.

Noël *et al.* now report surprising observations of the STO electron-gas system that adds to this complex behaviour. When the authors applied an electric field to the STO to control spin–orbit coupling in the gas, they observed a hysteresis effect – the direction of the charge current produced in the gas 'remembers' the polarity of the applied electric field, even after the field is removed (Fig. 1). Moreover, when they characterized the properties of the insulating STO beneath the gas, they observed features commonly attributed to ferroelectric compounds: when the polarity of the voltage applied across the STO is reversed, a spike of charge current is produced. Such a phenomenon is commonly associated with the reversal of electric dipoles in ferroelectric materials, and is at the core of the definition of electrical polarization in the modern theory of ferroelectricity[13].

The authors' system has potential applications for spintronics, because it acts as a spin detector, analogous to optical polarizers that transmit light polarized only along a particular direction. Moreover, when the polarity of the applied voltage is inverted, the selectivity of the spin filter changes so that electrons with 'spin up' polarization move right, instead of left. Crucially, this selectivity remains in the absence of an applied voltage. This minimizes power consumption and opens up applications for memory storage.

Ferroelectric-like behaviour has been observed previously in STO (see refs 14–16, for example). However, a peculiarity of the effect observed by Noël and colleagues is that it occurs only when the applied electric field exceeds a critical value. This raises concerns: true ferroelectric materials don't show polarization only at high fields; it is an intrinsic state that occurs even in the absence of an external electric field. Noël and colleagues' data indicate that something similar to a 'relaxor' state occurs in their system at low temperatures, in which a fraction of the STO consists of nanometre-scale domains that have an electrical polarization, and move or reorient in an applied electric field. By contrast, all of the material in a true ferroelectric compound is polarized.

One can speculate that the movement of polar walls[17] – boundaries that form between two STO domains that have different crystallographic orientations[18] – produces the spikes of current observed by Noël and co-workers. But other microscopic mechanisms might be at play, given the richness of STO's electronic behaviour; point defects produced in STO during the fabrication of the authors' device could also have a role. Research into the domain walls in STO is currently booming, and will probably find an explanation for the observed behaviour. In the meantime, the authors' demonstration of a permanent switch of spin–orbit coupling at a complex-oxide interface shows the potential of this class of material to compete in the race for more-efficient computing.

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1. Noël, P. *et al. Nature* **580**, 483–486 (2020).
2. *Nature* **479**, 309 (2011).
3. Moore, G. E. *Electronics* **38**, 114–117 (1965).
4. Abele, N. et al. *IEEE Int. Electron Devices Meet., 2005. IEDM Tech. Digest* 479–481 (2005).
5. Joshi, V. K. *Eng. Sci. Technol.* **19**, 1503–1513 (2016) .
6. Manipatruni, S., Nikonov, D. E. & Young, I. A. *Nature Phys.* **14**, 338–343 (2018).
7. Förg, B., Richter, C. & Mannhart, J. *Appl. Phys. Lett.* **100**, 053506 (2012).
8. Müller, K. A. & Burkard, H. *Phys. Rev. B* **19**, 3593–3602 (1979).
9. Bianchi, U., Kleemann, W. & Bednorz, J. G. *J. Phys. Condens. Matter* **6**, 1229 (1994).
10. Schooley, J. F., Hosler, W. R. & Cohen, M. L. *Phys. Rev. Lett.* **12**, 474–475 (1964).
11. Caviglia, A. D. *et al. Phys. Rev. Lett.* **104**, 126803 (2010).
12. Lesne, E. *et al. Nature Mater.* **15**, 1261–1266 (2016).
13. Resta, R. *Ferroelectrics* **136**, 51–55 (1992).
14. Sidoruk, J. *et al. Ferroelectrics* **505**, 200–209 (2016).
15. Manaka, H., Nozaki, H. & Miura, Y. *J. Phys. Soc. Jpn* **86**, 114702 (2017).
16. Hemberger, J., Lunkenheimer, P., Viana, R., Böhmer, R. & Loidl, A. *Phys. Rev. B* **52**, 13159–13162 (1995).
17. Schiaffino, A. & Stengel, M. F. *Phys. Rev. Lett.* **119**, 137601 (2017).
18. Honig, M. *et al. Nature Mater.* **12**, 1112–1118 (2013).