Condensed-matter physics

Dynamics of ferroelectric vortices revealed

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Vortices of electrical polarization have been observed to vibrate at extremely high frequencies in a material called a ferroelectric. Such motion could be directly controlled by electric fields for ultrafast data processing. See p.376

The ancient Greek philosopher Democritus viewed swirling vortices of matter, along with atoms, as fundamental components of the Universe. Nowadays, vortices are seen at all scales – from spiral galaxies and whirlpools to microscopic examples in superconductors and quantum fluids. Moreover, vortices have been found to greatly affect the properties of many materials, including superconductors, ferromagnets (materials exhibiting the familiar form of magnetism found in iron) and ferroelectrics (the electrical counterparts of ferromagnets). On page 376, Li *et al.*[1] report that vortices of electrical polarization in ferroelectrics can vibrate at terahertz-level frequencies (1 THz is 10^{12} Hz). The collective dynamics of such vortices potentially offer a platform for ultrafast data processing driven by electric fields.

Ferroelectrics have an intrinsic electrical polarization that is caused by a slight relative shift of positively and negatively charged ions in opposite directions. In nanometre-scale ferroelectrics, these ions not only interact with an applied electric field, but also produce a substantial internal electric field owing to charges arising at the material surfaces. The resulting self-interaction of the ions through this internal field generates a plethora of polarization patterns – such as vortices and intricate structures called skyrmions and hopfions. Until now, the dynamics of these polarization patterns had been conjectured[2–5], but not demonstrated experimentally.

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To address this lack, Li and colleagues used a structure called a ferroelectric superlattice, which consists of stacked alternating films of a ferroelectric and an electrical insulator. Since the dawn of solid-state physics[6,7], it has been known that magnetic films harbour periodic domains of alternating oppositely oriented magnetization. But it was recognized only in the past few decades that similar polarization domains arise in ferroelectrics. The polarization pattern is more elaborate in ferroelectric superlattices than in isolated ferroelectrics, and gradually changes between domains[8]. Moreover, this pattern has been shown experimentally to evolve into a periodic system of vortices and antivortices (whirls that rotate in the opposite direction to vortices)[9].

The authors used ultrashort pulses of terahertz radiation to generate vortex motion in the ferroelectric films of the superlattice. They then used a technique known as ultrafast X-ray diffraction to probe the dynamics of the periodic vortex–antivortex structure. These state-of-the-art experimental methods allowed Li *et al.* to induce and analyse the collective movement of the polarization vortices directly on picosecond timescales (1 ps is 10^{-12} s). The authors detected a single mode of vibration at 0.08 THz and a set of such modes at 0.3–0.4 THz.

In terms of dynamics, the vortex–antivortex system (Fig. 1a) resembles a linear chain of balls connected by elastic springs. The role of elastic forces is taken by electrostatic interactions between the ions that maintain vortex periodicity. The system can host two types of collective vibration, an up-and-down (transverse) motion (Fig. 1b) and a side-to-side (longitudinal) motion (Fig. 1c).

Li *et al.* attributed their detected 0.08-THz

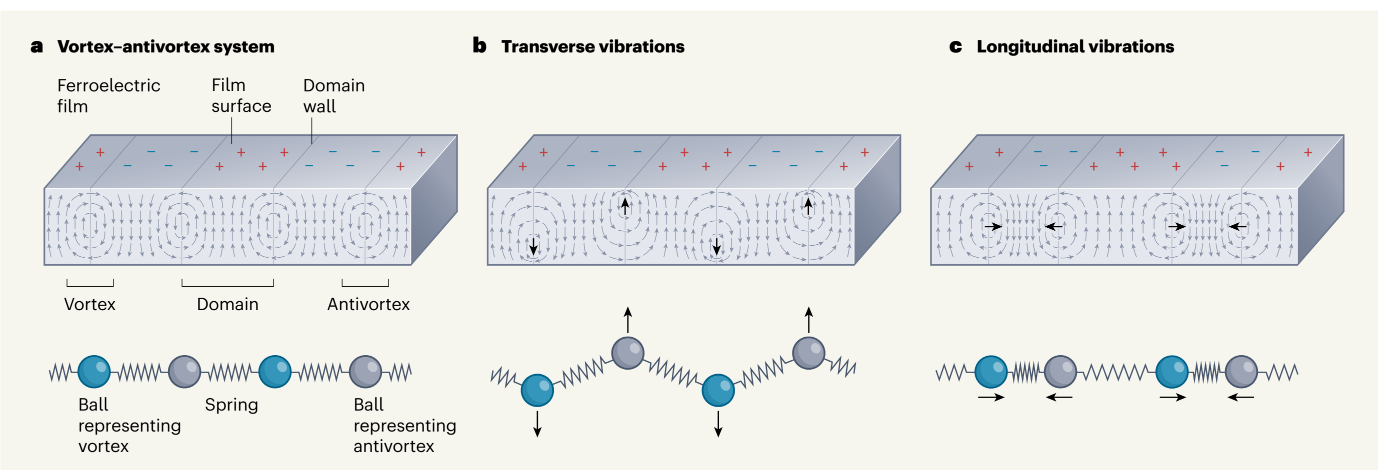

Figure 1 | Polarization vortices in a ferroelectric film. a, A film of a material known as a ferroelectric contains domains separated by boundaries called domain walls. Adjacent domains carry opposite charges (indicated by plus and minus symbols) on the film surface. In the equilibrium state, these positive and negative charges have equal magnitude. The pattern of electrical polarization (shown by arrows) is a periodic system of vortices and antivortices (whirls that rotate in the opposite direction to vortices). The dynamics of this system have been investigated by Li *et al.*[1] and can be modelled by a chain of balls connected by springs. **b**, The vortex–antivortex system can undergo transverse vibrations (indicated by black arrows). The domain walls do not move, and the magnitudes of the surface charges remain balanced. **c**, The system can also undergo longitudinal vibrations (indicated by black arrows). The associated displacements of domain walls cause the positive and negative surface charges to differ in magnitude.

mode to transverse vibrations. This previously unseen vortex motion indicates that an instability accompanies a structural transition to a state in which the vortex centres form a zigzag chain. Compared with the 0.08-THz mode, those at 0.3–0.4 THz are associated with more-intricate vortex dynamics and can be less easily attributed to a particular type of vibration.

To unravel the full picture of vortex dynamics, future work needs to distinguish between inter-vortex motion, intra-vortex motion and vortex bending. Moreover, the longitudinal mode of vibration must be identified. This mode is associated with a sequence of alternating displacements of domain walls (the boundaries between domains) and has remarkable properties that arise from the associated dynamics of surface charges.

In metals, surface charges oscillate at frequencies corresponding to ultraviolet light (about 10^{15} Hz), and the collective oscillations are known as plasmons. Similarly, in a ferroelectric film, the longitudinal mode causes surface charges to oscillate at terahertz frequencies, and the collective oscillations can be thought of as polarization plasmons. In such a film, as in metals, a quantity called the dielectric constant is negative when the frequency of an applied electric field is lower than the plasmon oscillation frequency. Surprisingly, the dielectric constant in the ferroelectric film remains negative as the frequency of the applied field tends to zero, resulting in a negative-capacitance effect[5] – a phenomenon that promises to reduce the power consumption of next-generation nanoscale electronic devices.

The past decade has seen remarkable progress in developing terahertz semiconductor devices, working in the frequency range between radio waves and infrared light. The potential applications of these devices span wireless transmission of vast amounts of data, detection of distant security threats, 6G wireless technology and opportunities for non-invasive medical imaging. Li and colleagues' discovery that polarization vortices in nanoscale ferroelectric films can vibrate at terahertz-level frequencies could help to scale down terahertz devices to the nanoscale and achieve high-speed, high-density data processing driven by electric fields. Such advances might enable the development of terahertz optoelectronics and plasmonics (plasmon-based photonics), ultrafast data exchange and intra-chip communications in emerging computer circuits.

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Neuroscience

A critical period that shapes motor circuits

Laura Sancho & Nicola J. Allen

A mechanism has been found in fruit flies that enables cells called astrocytes to signal to neurons, closing a developmental window during which locomotor behaviour is shaped. **See p.414**

There are times in an organism's development when parts of the forming nervous system are particularly sensitive to changing inputs. Disrupting these critical periods can have lifelong effects on neuronal connectivity and brain function[1]. For example, there is a critical period during childhood for language acquisition[2]. And altered critical periods have been suggested to play a part in neurodevelopmental disorders, including autism spectrum disorder[3] and schizophrenia[4]. Critical periods have been extensively described in the visual system[1], but, until now, there has been less focus on non-sensory systems. Ackerman *et al.*[5] close this gap on page 414. The authors identify a critical period for motor-circuit development in the fruit fly *Drosophila melanogaster*, and establish the cellular and molecular underpinnings of critical-period closure in this system.

During a critical period, neuronal connections can be reshaped in several ways. Ackerman *et al.* mainly address homeostatic plasticity, in which changes occur across an entire neuron – including in the size of structures called dendrites, which receive synaptic connections from other neurons, in synapse numbers and in the strength of electrical impulses transmitted by synapses[6].

First, the authors used a technique called optogenetics to activate or inhibit neuronal activity in two classes of neuron called aCC and RP2 motor neurons. When they silenced the neurons, both the length and volume of the cells' dendrites increased. By contrast, optogenetic activation led to dendritic retraction. These changes occurred only when neuronal activity was manipulated in the 8 hours after larval hatching, and just 15 minutes of manipulation was necessary to see effects.

Next, Ackerman and colleagues asked if the changes in dendrite shape translated into changes in the numbers of excitatory and inhibitory synaptic connections on the aCC and RP2 motor neurons (these synapses activate and inhibit neuronal activity, respectively). Optogenetic silencing of the neurons resulted in a reduction in inhibitory-synapse numbers and an increase in excitatory synapses. Together, the expansion of dendrites and the shift in synapse composition allowed the neurons to rebalance neuronal activity, counteracting the effect of optogenetic silencing. Optogenetic activation of aCC and RP2 neurons led to a decrease in the number of excitatory synapses, but not to an increase in inhibitory synapses, perhaps owing to the limited amount of cell membrane available for the formation of connections after dendrite retraction. Together, this first batch of findings indicates that there is a critical period for homeostatic changes to dendritic structure and synapse number in the developing motor system of *D. melanogaster* (Fig. 1a, b).

What induces these changes? Neurons are often in close contact with cells called astrocytes, which help to regulate synaptic development and maintain brain function[7]. Ackerman *et al.* therefore used genetic engineering to eliminate all astrocytes in their fruit flies. Dendritic remodelling continued beyond eight hours after larval hatching in the mutant flies, but there was no increase in the amount of remodelling that occurred before the eight-hour period had elapsed. These findings indicate that astrocytes regulate the timing of critical-period closure for the aCC/RP2 system, but not the potential for plasticity during this time. This is a key distinction, because it suggests that different