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. ■

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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,

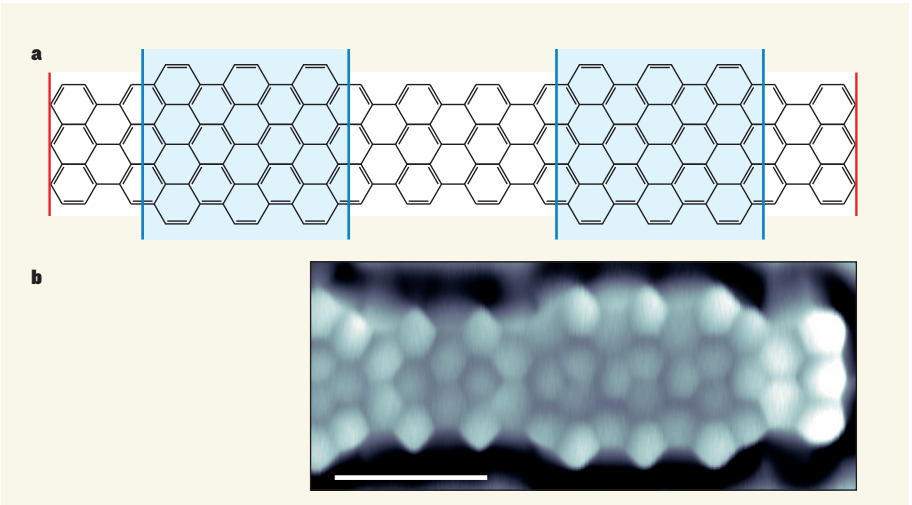


IMAGE: D. J. RIZZO *ET AL.*/*NATURE*

**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.

over the past decade or so, researchers have learnt that this picture needs to be amended in fundamental ways. This realization has led to the discovery of materials known as topological insulators, which are insulating in their interior but robustly conducting on their boundaries[4]. Correspondingly, these materials have an energy gap in their interior, but are gapless on their boundaries. This behaviour reflects beautiful, albeit somewhat abstract, topological properties of the materials' electronic states.

Rizzo *et al.* and Gröning *et al.* have experimentally demonstrated that graphene nanoribbons can be used to produce such topological states. Defect-free graphene nanoribbons can be grown on metallic substrates in a remarkably flexible manner[5]. Starting with cleverly designed precursor molecules, the nanoribbons' terminations and widths can be controlled with single-atom precision. The authors used this synthesis technique to grow nanoribbons that alternate in width (Fig. 1a).

The widths were chosen such that the nanoribbons consist of alternating topologically trivial and non-trivial segments. Whenever two materials of different topology are brought into contact, gapless states must form at the interface. Consequently, such states are produced at the junctions between the nanoribbon segments. Because nanoribbons are essentially one-dimensional, each of these gapless junction states is simply an individual electron orbital localized in the vicinity of the intersection.

But the topology of the nanoribbons does not stop here. Rizzo *et al.* and Gröning *et al.* used the junction states as building blocks to engineer yet another system. This system is closely related to an archetypal model of electronic topology known as the Su–Schrieffer–Heeger (SSH) model, which emerged in the late 1970s from the study of organic conductors such as polyacetylene[6].

Although the SSH model is simple, it has remarkable properties. In particular, a finite chain of electronic orbitals described by the SSH model can have gapless topological states localized at its ends. The crucial ingredient in the model is an alternation of weak and strong bonds between neighbouring electron orbitals.

In the authors' nanoribbons, adjacent gapless junction states straddle narrow or wide regions of the material. The coupling of these states is stronger across the wide regions than across the narrow regions, producing exactly the bond alternation that underlies the SSH model. Such a coupling is therefore expected to generate topological states at the ends of the nanoribbons, assuming that these materials are suitably designed[1].

Rizzo *et al.* and Gröning *et al.* confirmed this theoretical prediction to an impressive degree. The authors used a combination of scanning tunnelling microscopy and spectroscopy to probe and visualize the electronic properties of the nanoribbons with atomic-scale spatial resolution (Fig. 1b). They observed the junction states — which formed broadened energy bands as a result of their coupling — and the end states associated with the bond alternation. Of note is the fact that the authors grew and probed their nanoribbons on a highly conducting gold substrate, which effectively weakens the electric forces between the electrons in the nanoribbons. Without such a conducting substrate, these forces could be substantial, and might produce additional interesting physics[1].

Beyond fabricating these specific nanoribbons and exploring their electronic topologies, the two studies reveal several key insights. For instance, the production of topological electronic materials is often hampered by sample imperfections. Frequently, defects induce a large internal conductivity, even if the material is nominally a topological insulator. This problem is particularly severe in 1D systems, in which the electrons cannot circumvent defects. Such systems are often fabricated using a top-down approach, in which the materials are patterned from larger structures. A promising avenue for alleviating the issue of sample imperfections is to produce the systems by means of a bottom-up method, such as that used by the authors, in which the materials are made by chemical processes.

These studies also highlight the potential of using topological boundary states for materials engineering. This idea can be extended to higher dimensions than the authors' 1D system, for instance to periodic 'superlattices' made of alternating topologically trivial and non-trivial layers. Finally, the authors suggest that, when in contact with a superconductor, the nanoribbons could act as a topological superconductor — another fascinating class of topological electronic state that might have applications in quantum computing. ■

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IMMUNOLOGY

# Making mitochondrial DNA is inflammatory

**Activation of the inflammasome protein complex in immune cells is a key step that triggers an innate immune response. It emerges that the synthesis and oxidation of mitochondrial DNA drives this activation step.** SEE ARTICLE P.198

MICHAEL P. MURPHY

The innate immune response mounts a defence when immune cells recognize general hallmarks of infection, such as lipopolysaccharide (LPS) molecules, which are present in many types of bacterium. However, the inappropriate unleashing of an innate immune response can lead to autoimmune disorders. Gaining a better understanding of how innate immune responses are regulated might lead to improvements in clinical treatments for such disorders. On page 198, Zhong *et al.*[1] report that DNA synthesis in organelles called mitochondria has a key role in triggering an innate immune response

Mitochondria can regulate how immune cells respond to infection and tissue damage. For example, these organelles can produce pro- or anti-inflammatory signals by altering the levels of metabolites produced in the Krebs cycle[2,3], or by changing the level of production of reactive oxygen species (ROS)[4,5]. More and more examples are being found of mitochondrial functions being repurposed in unexpected ways to contribute to inflammatory signalling[2–5].

The inflammasome is a multiprotein complex that assembles in immune cells during an innate immune response. It provides defensive functions when the inflammasome-associated enzyme caspase-1 cleaves and activates inflammatory proteins such as IL-1β. Inflammasomes that contain the protein NLRP3 can form in immune cells called macrophages, and the initial steps in the assembly or priming of this type of inflammasome are reasonably well understood: if LPS binds to the receptor protein TLR4 on the macrophage surface, there is an increase in signalling by the NF-κB pathway. This causes an increase in expression of NLRP3 and of the precursor form of IL-1β.

However, the process that triggers inflammasome activation, which occurs when the enzyme caspase-1 is recruited to