A simpler approach for creating quantum materials

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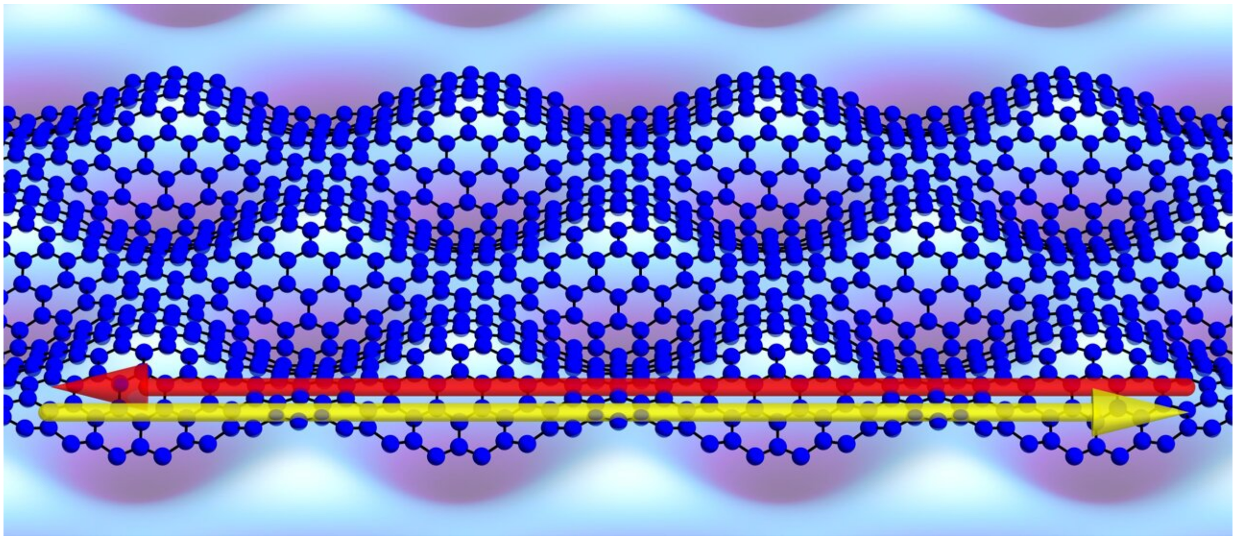

A depiction of a carefully-designed substrate that causes a deposited sheet of graphene to ripple. This distortion generates currents that reside on only one side of the nanoribbon structure. Credit: Võ Tiến Phong

Since graphene was first isolated and characterized in the early 2000s, researchers have been exploring ways to use this atomically thin nanomaterial because of its unique properties such as high tensile strength and conductivity.

In more recent years, twisted bilayer graphene, made of two sheets of graphene twisted to a specific "magic" angle, has been shown to have superconductivity, meaning that it can conduct electricity with very little resistance. However, using this approach to make devices remains challenging because of the low yield of fabricating twisted bilayer graphene.

Now, a new study shows how patterned, periodic deformations of a single layer of graphene transforms it into a material with electronic properties previously seen in twisted graphene bilayers. This system also hosts additional unexpected and interesting conducting states at the boundary. Through a better understanding of how unique properties occur when single sheets of graphene are subjected to periodic strain, this work has the potential to create quantum devices such as orbital magnets and superconductors in the future. The study, published in *Physical Review Letters*, was conducted by graduate student Võ Tiến Phong and professor Eugene Mele in Penn's Department of Physics & Astronomy in the School of Arts & Sciences.

One alternative to the complex twisted bilayer method is to use single layers of graphene that are placed onto a carefully-patterned substrate, known as a "bed of nails," which applies an external force, or strain, in a periodic fashion. To better understand the quantum geometrical properties of this system, Mele and Phong set out to understand the theory underlying how electrons move in this single-layered system.

After running computer simulations of single-layered experiments, the researchers were surprised to find new evidence of unexpected phenomena along the surface of the material but only along one side. "Generally, topology in the bulk associates with surface properties, and when that's the case all surfaces inherit the property," says Mele. "Here, the fact that there were edge modes on one side and not the other struck me as being deeply unusual."

This finding was unexpected because in this system the average pseudomagnetic field, induced when the system is strained, was zero—positive in one area but negative in the other, which the researchers hypothesized would cancel out any unique phenomena. "If the magnetic field is zero, you probably won't get any interesting physics," says Phong. "On the contrary, we found that even though the average magnetic field is zero, it still gives you some interesting physics at the edge."

To explain this unexpected result, Phong took a closer look at a similar experimental system where single sheets of graphene are bent to simulate a constant instead of periodic strain induced field. Phong found that this system had the same topological index, meaning that edge states that only thrive on a specific side of the material would also occur. "The physics here was similar and seemed to be the right explanation for the phenomenology we were working on," Phong says.

Overall, this study predicts that flat bands, similar to the ones found in twisted bilayer graphene, are created by depositing an atomically thin single layer onto a bed-of-nails substrate that induces a periodic distortion on the graphene sheet.

The researchers are already progressing towards an even deeper understanding of these single-layered systems. One avenue of further research involves a collaboration with assistant professor Bo Zhen to study the same phenomenon using light waves. The researchers are also interested in seeing if other unique properties that exist in twisted bilayer graphene might also occur within single-layer systems.

"Although the physics is simple, meaning that you can get the system to behave the way you want in a more controlled way, the phenomenology that you can get out of it is not. It's very rich, and we're still uncovering new things as we speak," Phong says.

And because these single-layer systems are simpler to work with, this enhanced theoretical understanding has the potential to aid in future discoveries in the field of edge state physics, including possible new devices such as ultra-small, incredibly fast quantum materials.

"There's a huge effort right now to understand these twisted graphene bilayers, and I think an interesting question we're nailing here is the essential ingredients of a physical system that could actually do that," says Mele. "We're building artificial structures that you couldn't build from the top down at an interesting length scale—bigger than atoms, smaller than you can do by lithography—and, if you have control of that, there's a lot of things you can do."

More information: Võ Tiến Phong et al, Boundary Modes from Periodic Magnetic and Pseudomagnetic Fields in Graphene, *Physical Review Letters* (2022). DOI: 10.1103/PhysRevLett.128.176406

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