Newly discovered graphene property could impact next-generation computing

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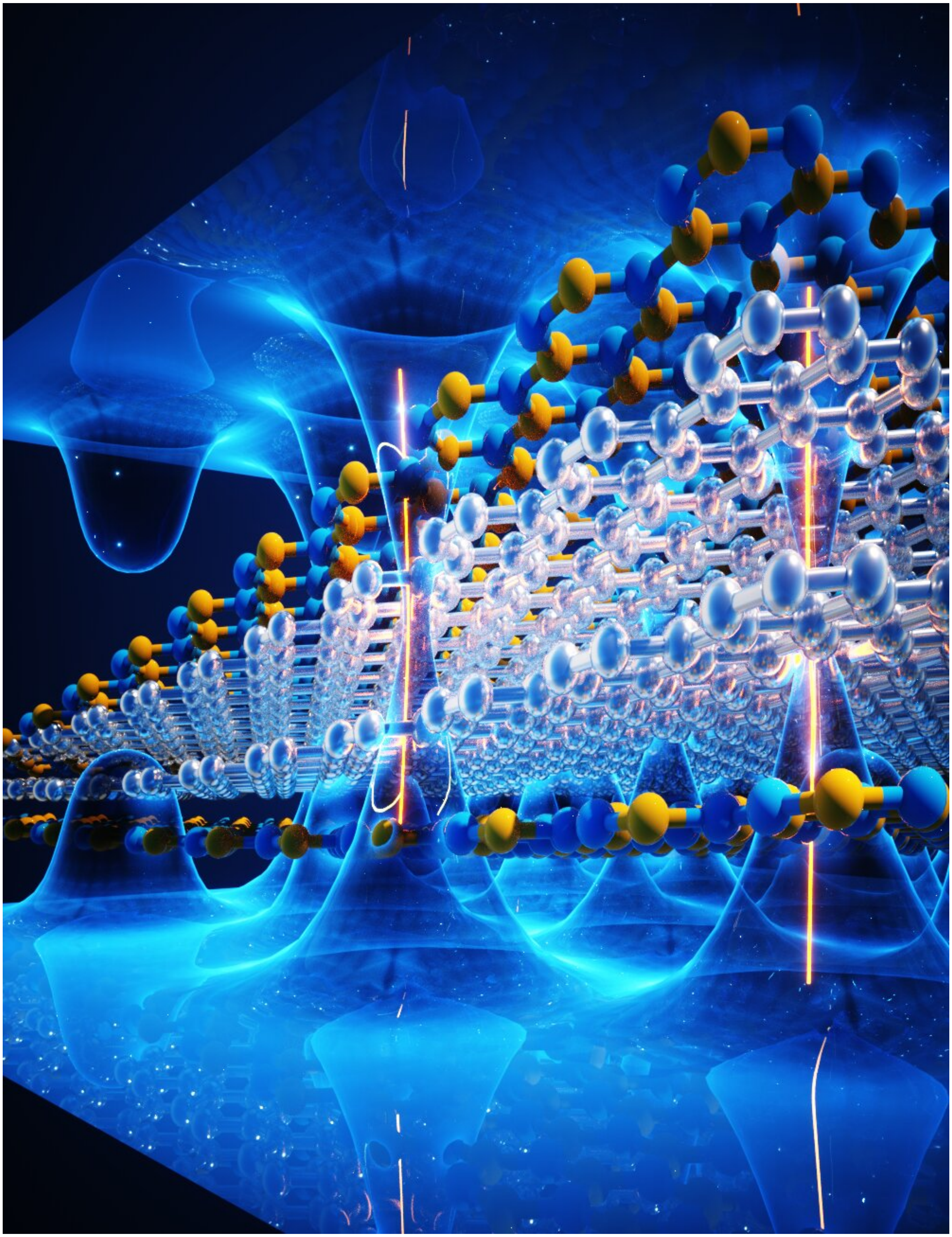


Artist’s representation of the nanoscopic structure of the new ferroelectric material developed by MIT researchers and colleagues. Blue and gold dots represent the boron and nitride atoms in two atomically thin sheets of boron nitride. Between these sheets are two layers of graphene; the whitish/blue dots represent carbon atoms. The gold vertical lines running through the figure represent the movement of electrons. Credit: Schematic by Ella Maru Studio

MIT researchers and colleagues have discovered an important—and unexpected—electronic property of graphene, a material discovered only about 17 years ago that continues to surprise scientists with its interesting physics. The work, which involves structures composed of atomically thin layers of materials that are also biocompatible, could usher in new, faster information-processing paradigms. One potential application is in neuromorphic computing, which aims to replicate the neuronal cells in the body responsible for everything from behavior to memories.

The work also introduces new physics that the researchers are excited to explore.

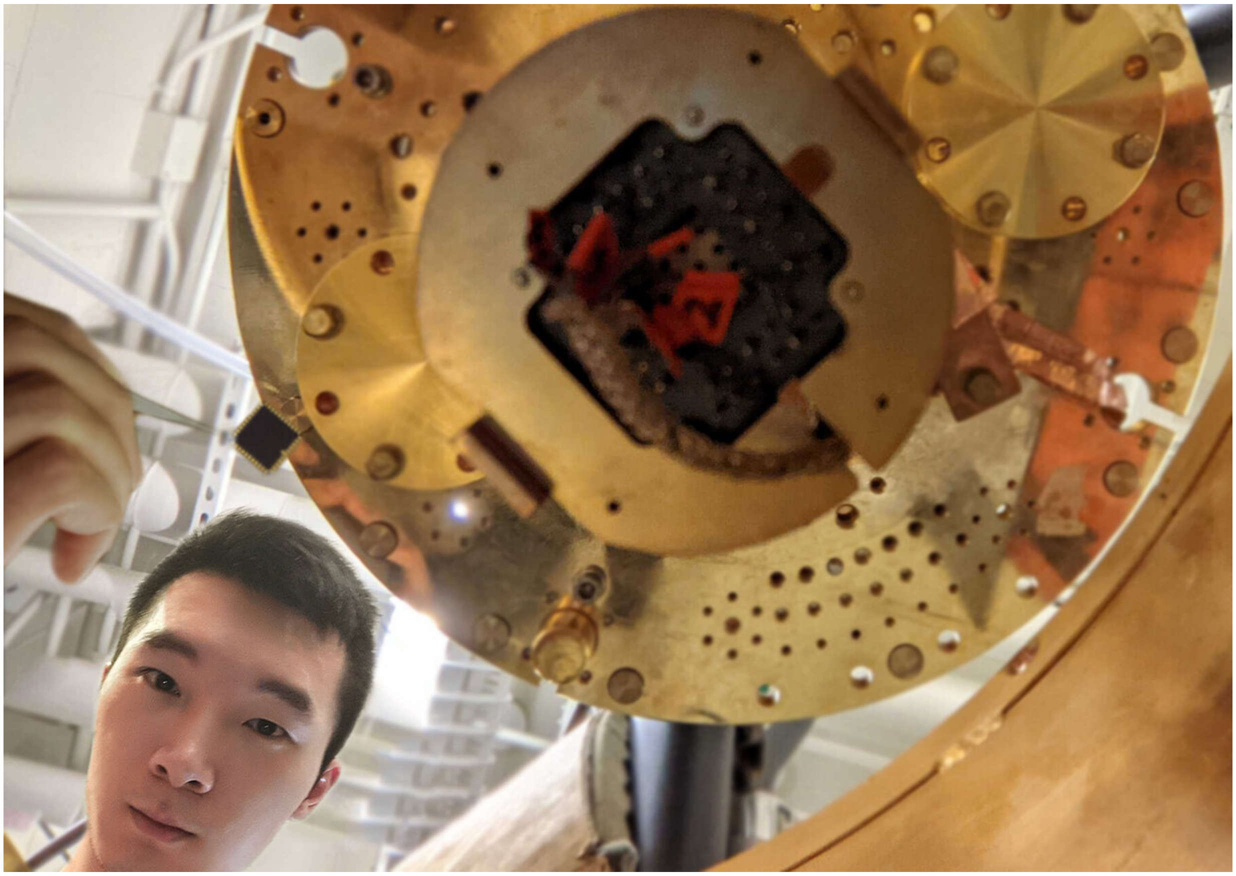
"Graphene-based heterostructures continue to produce fascinating surprises. Our observation of unconventional ferroelectricity in this simple and ultra-thin system challenges many of the prevailing assumptions about ferroelectric systems and it may pave the way for an entire generation of new ferroelectrics materials," says Pablo Jarillo-Herrero, the Cecil and Ida Green Professor of Physics at MIT and leader of the work, which involved a collaboration with five other MIT faculty from three departments.

A New Property

Graphene is composed of a single layer of carbon atoms arranged in hexagons resembling a honeycomb structure. Since the material's discovery, scientists have shown that different configurations of graphene layers can give rise to a variety of important properties. Graphene-based structures can be either superconductors, which conduct electricity without resistance, or insulators, which prevent the movement of electricity. They have even been found to display magnetism.

In the current work, which was reported last December in *Nature*, the MIT researchers and colleagues show that bilayer graphene can also be ferroelectric. This means that positive and negative charges in the material can spontaneously separate into different layers.

In most materials, opposite charges are attracted to each other; they want to combine. Only the application of an electric field will force them to opposite sides, or poles. In a ferroelectric material, no external electric field is necessary to keep the charges apart, giving rise to a spontaneous polarization. However, the application of an external electric field does have an effect: an electric field of opposite direction will cause the charges to switch sides and reverse the polarization.



Zhiren (Isaac) Zheng holds up a sample of the new ferroelectric structure created by MIT researchers and colleagues (small black square with gold edges above Zheng's head). The gold structure is the inside of a Cryogen Free Dilution Refrigerator that the researchers used to measure the new ferroelectric structures. Credit: Sergio de la Barrera, MIT

For all of these reasons, ferroelectric materials are used in a variety of electronic systems, from medical ultrasounds to radio frequency identification (RFID) cards.

Conventional ferroelectrics, however, are insulators. The MIT-led team's ferroelectric based on graphene operates through a completely different mechanism—different physics—that allows it to conduct electricity.

And that opens up myriad additional applications. "What we've found here is a new type of ferroelectric material," says Zhiren (Isaac) Zheng, an MIT graduate student in physics and first author of the Nature paper.

Qiong Ma, MIT Ph.D. 2016, a co-author of the paper and an assistant professor at Boston College, puts the work in perspective. "There are challenges associated with conventional ferroelectrics that people have been working to overcome. For example, the ferroelectric phase becomes unstable as the device continues to be miniaturized. With our material, some of those challenges may be automatically solved." Ma conducted the current work as a postdoctoral associate through MIT's Materials Research Laboratory (MRL).

Important Patterns

The structure the team created is composed of two layers of graphene—a bilayer—sandwiched between atomically thin layers of boron nitride (BN) above and below. Each BN layer is at a slightly different angle from the other. Looking from above, the result is a unique pattern called a moiré superlattice. A moiré pattern, in turn, "can dramatically change the properties of a material," Zheng says.

Jarillo-Herrero's group demonstrated an important example of this in 2018. In that work, also reported in *Nature*, the researchers stacked two layers of graphene. Those layers, however, weren't exactly on top of each other; rather, one was slightly rotated at a "magic angle" of 1.1 degrees. The resulting structure created a moiré pattern that in turn allowed the graphene to be either a superconductor or an insulator depending on the number of electrons in the system as provided by an electric field. Essentially the team was able to "tune graphene to behave at two electrical extremes," according to an MIT news story at the time.

"So by creating this moiré structure, graphene is not graphene anymore.

It almost magically turns into something very, very different," Ma says.

In the current work, the researchers created a moiré pattern with sheets of graphene and boron nitride that has resulted in a new form of ferroelectricity. The physics involved in the movement of electrons through the structure is different from that of conventional ferroelectrics.

"The ferroelectricity demonstrated by the MIT group is fascinating," says Philip Kim, a Professor of Physics and Applied Physics at Harvard University, who was not involved in the research.

"This work is the first demonstration that reports pure electronic ferroelectricity, which exhibits charge polarization without ionic motion in the underlying lattice. This surprising discovery will surely invite further studies that can reveal more exciting emergent phenomena and provide an opportunity to utilize them for ultrafast memory applications."

The researchers aim to continue the work by not only demonstrating the new material's potential for a variety of applications, but also developing a better understanding of its physics. "There are still many mysteries that we don't fully understand and that are fundamentally very intriguing," Ma says.

More information: Zhiren Zheng et al. Unconventional ferroelectricity in moiré heterostructures, *Nature* (2020). DOI: 10.1038/s41586-020-2970-9

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