Graphene shows strange new behavior better suited for electronic devices

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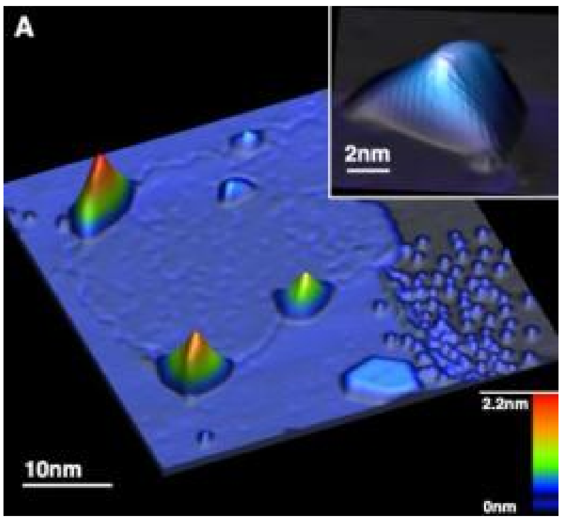


This is a scanning tunneling microscope image of a single layer of graphene on platinum with four nanobubbles at the graphene-platinum border and one in the patch interior. The inset shows a high-resolution image of a graphene nanobubble and its distorted honeycomb lattice due to strain in the bubble. Credit: Crommie lab, UC Berkeley

Regarded as a possible replacement for silicon-based semiconductors, graphene, a sheet of pure carbon, has been discovered to have an uncommon and astonishing property that might make it better matched for future electronic devices.

Physicists at the University of California, Berkeley, and the Lawrence

Berkeley National Laboratory (LBNL) have found stretching graphene in a specific way produces nanobubbles, forcing electrons to behave as if a strong magnetic field is moving them.

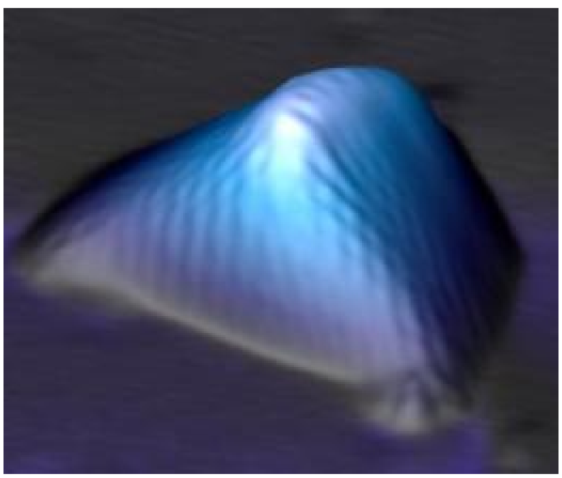
Instead of utilizing energy bands, as in unstrained graphene, the electrons within each individual nanobubble sperate into quantized energy levels. "The energy levels are identical to those that an electron would occupy if it were moving in circles in a very strong magnetic field; as high as 300 tesla, which is bigger than any laboratory can produce except in brief explosions," said Michael Crommie, professor of physics at UC Berkeley and faculty researcher at LBNL. "This gives us a new handle on how to control how electrons move in graphene, and thus to control graphene's electronic properties, through strain. By controlling where the electrons bunch up and at what energy, you could cause them to move more easily or less easily through graphene, in effect, controlling their conductivity, optical or microwave properties. Control of electron movement is the most essential part of any electronic device."

While the Earth's magnetic field at ground level is 31 microtesla, magnetic resonance imagers use magnets less than 10 tesla. Crommie and colleagues will report the discovery in the July 30 issue of the journal *Science*.

Crommie is eager to use the abnormal property of graphene to investigate how electrons function in fields that, until now, have not been obtained in the laboratory, despite the engineering implications of the discovery. "When you crank up a magnetic field you start seeing very interesting behavior because the electrons spin in tiny circles," he said. "This effect gives us a new way to induce this behavior, even in the absence of an actual magnetic field."

Among the strange behaviors observed of electrons in strong magnetic fields are the quantum Hall effect and the fractional quantum Hall effect, when low temperatures electrons also fall into quantized energy levels.

Discovered by accident, the new effect was found when a UC Berkeley postdoctoral researcher and students in Crommie's lab grew graphene on the surface of a platinum crystal. Much like chicken wire, graphene is a one atom-thick sheet of carbon atoms arranged in a hexagonal pattern. When grown on platinum, the carbon atoms do not line up with the metal surface's triangular crystal structure. this, in turn, creates a strain pattern in the graphene as if it were pulled from three different directions.



In this scanning tunneling microscopy image of a graphene nanobubble, the hexagonal two-dimensional graphene crystal is seen distorted and stretched along three main axes. The strain creates pseudo-magnetic fields far stronger than any magnetic field ever produced in the laboratory Credit: courtesy of Micheal Crommie, Berkeley Lab

"The strain produces small, raised triangular graphene bubbles 4 to 10 nanometers across in which the electrons occupy discrete energy levels rather than the broad, continuous range of energies allowed by the band structure of unstrained graphene. This new electronic behavior was detected spectroscopically by scanning tunneling microscopy. These so-called Landau levels are reminiscent of the quantized energy levels of electrons in the simple Bohr model of the atom," Crommie said.

First predicted for carbon nanotubes in 1997 by Charles Kane and Eugene Mele of the University of Pennsylvania, was the appearance of a pseudomagnetic field in response to strain in graphene. Nanotubes are merely a rolled up form of graphene.

However, within the last year, Francisco Guinea of the Instituto de Ciencia de Materiales de Madrid in Spain, Mikhael Katsnelson of Radboud University of Nijmegen, the Netherlands, and A. K. Geim of the University of Manchester, England predicted a pseudo quantum Hall effect in strained graphene. This is the same quantization that Crommie's research group has observed. Visiting Crommie's laboratory at the time of discovery, Boston University physicist, Antonio Castro Neto, immediately recognized the data's implications. Subsequent experiments confirmed, it reflected the pseudo quantum Hall effect as predicted.

"Theorists often latch onto an idea and explore it theoretically even before the experiments are done, and sometimes they come up with predictions that seem a little crazy at first. What is so exciting now is that we have data that shows these ideas are not so crazy," Crommie said. "The observation of these giant pseudomagnetic fields opens the door to room-temperature 'straintronics,' the idea of using mechanical deformations in graphene to engineer its behavior for different electronic device applications."

Crommie also noted, the "pseudomagnetic fields" inside the nanobubbles are high enough that the energy levels are separated by hundreds of millivolts, which is much higher than room temperature. Even at room temperature, thermal noise would not interfere with this effect in graphene. However, the nanobubble experiments performed in Crommie's laboratory were performed at very low temperatures.

Electrons moving in a magnetic field would normally circle around the field lines, but within the strained nanobubbles, the electrons circle in the plane of the graphene sheet. It's as if a strong magnetic field was applied perpendicular to the sheet, even when there is no actual magnetic field. "Apparently," Crommie said, "the pseudomagnetic field only affects moving electrons and not other properties of the electron, such as spin, that are affected by real magnetic fields."

Source: University of California - Berkeley

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