

Scientists create world's thinnest magnet

July 20 2021

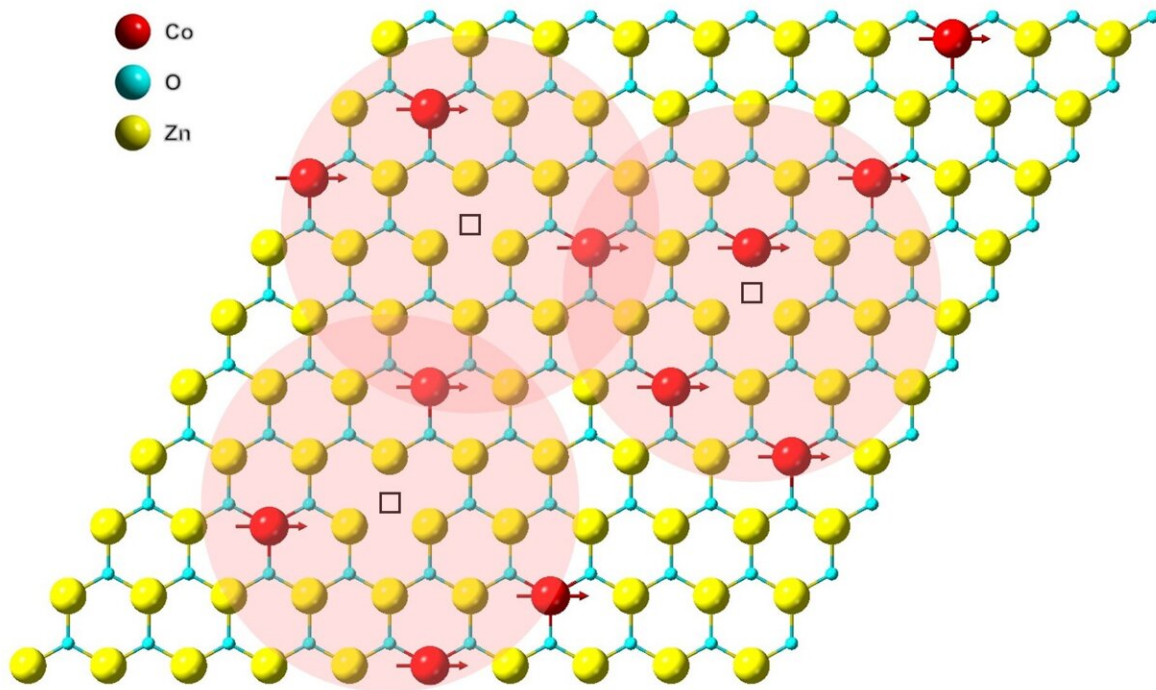


Illustration of magnetic coupling in a cobalt-doped zinc-oxide monolayer. Red, blue, and yellow spheres represent cobalt, oxygen, and zinc atoms, respectively. Credit: Berkeley Lab

The development of an ultrathin magnet that operates at room

temperature could lead to new applications in computing and electronics—such as high-density, compact spintronic memory devices—and new tools for the study of quantum physics.

The ultrathin magnet, which was recently reported in the journal *Nature Communications*, could make big advances in next-gen memories, computing, spintronics, and quantum physics. It was discovered by scientists at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and UC Berkeley.

"We're the first to make a [room-temperature](#) 2-D magnet that is chemically stable under ambient conditions," said senior author Jie Yao, a faculty scientist in Berkeley Lab's Materials Sciences Division and associate professor of materials science and engineering at UC Berkeley.

"This discovery is exciting because it not only makes 2-D magnetism possible at room temperature, but it also uncovers a new mechanism to realize 2-D magnetic materials," added Rui Chen, a UC Berkeley graduate student in the Yao Research Group and lead author on the study."

The magnetic component of today's memory devices is typically made of magnetic thin films. But at the atomic level, these magnetic films are still three-dimensional—hundreds or thousands of [atoms](#) thick. For decades, researchers have searched for ways to make thinner and smaller 2-D magnets and thus enable data to be stored at a much higher density.

Previous achievements in the field of 2-D [magnetic materials](#) have brought promising results. But these early 2-D magnets lose their [magnetism](#) and become chemically unstable at room temperature.

"State-of-the-art 2-D magnets need very low temperatures to function. But for practical reasons, a data center needs to run at room

temperature," Yao said. "Theoretically, we know that the smaller the magnet, the larger the disc's potential data density. Our 2-D magnet is not only the first that operates at room temperature or higher, but it is also the first magnet to reach the true 2-D limit: It's as thin as a single atom!"

The researchers say that their discovery will also enable new opportunities to study quantum physics. "Our atomically thin magnet offers an optimal platform for probing the quantum world," Yao said. "It opens up every [single atom](#) for examination, which may reveal how quantum physics governs each single magnetic atom and the interactions between them. With a conventional bulk magnet where most of the magnetic atoms are deeply buried inside the material, such studies would be quite challenging to do."

The making of a 2-D magnet that can take the heat

The researchers synthesized the new 2-D magnet—called a cobalt-doped van der Waals zinc-oxide magnet—from a solution of graphene oxide, zinc, and cobalt. Just a few hours of baking in a conventional lab oven transformed the mixture into a single atomic layer of zinc-oxide with a smattering of cobalt atoms sandwiched between layers of graphene. In a final step, graphene is burned away, leaving behind just a single atomic layer of cobalt-doped zinc-oxide.

"With our material, there are no major obstacles for industry to adopt our solution-based method," said Yao. "It's potentially scalable for mass production at lower costs."

To confirm that the resulting 2-D film is just one atom thick, Yao and his team conducted scanning electron microscopy experiments at Berkeley Lab's Molecular Foundry to identify the material's morphology, and transmission electron microscopy imaging to probe the material

atom by atom.

With proof in hand that their 2-D material really is just an atom thick, the researchers went on to the next challenge that had confounded researchers for years: Demonstrating a 2-D magnet that successfully operates at room temperature.

X-ray experiments at Berkeley Lab's Advanced Light Source characterized the 2-D material's magnetic parameters under high temperature. Additional X-ray experiments at SLAC National Accelerator Laboratory's Stanford Synchrotron Radiation Lightsource verified the electronic and crystal structures of the synthesized 2-D magnets. And at Argonne National Laboratory's Center for Nanoscale Materials, the researchers imaged the 2-D material's crystal structure and chemical composition using [transmission electron microscopy](#).

As a whole, the research team's lab experiments showed that the graphene-zinc-oxide system becomes weakly magnetic with a 5-6% concentration of cobalt atoms. Increasing the concentration of cobalt atoms to about 12% results in a very strong magnet.

To the researchers' surprise, a concentration of cobalt atoms exceeding 15% shifts the 2-D magnet into an exotic quantum state of "frustration," whereby different magnetic states within the 2-D system are in competition with each other.

And unlike previous 2-D magnets, which lose their magnetism at room temperature or above, the researchers found that the new 2-D magnet not only works at room temperature but also at 100 degrees Celsius (212 degrees Fahrenheit).

"Our 2-D magnetic system shows a distinct mechanism compared to previous 2-D magnets," said Chen. "And we think this unique

mechanism is due to the [free electrons](#) in zinc oxide."

True north: Free electrons keep magnetic atoms on track

When you command your computer to save a file, that information is stored as a series of ones and zeroes in the computer's magnetic memory, such as the magnetic hard drive or a flash memory. And like all magnets, magnetic memory devices contain microscopic magnets with two poles—north and south, the orientations of which follow the direction of an external magnetic field. Data is written or encoded when these tiny magnets are flipped to the desired directions.

According to Chen, zinc oxide's free electrons could act as an intermediary that ensures the magnetic cobalt atoms in the new 2-D device continue pointing in the same direction—and thus stay magnetic—even when the host, in this case the semiconductor zinc oxide, is a nonmagnetic material.

"Free electrons are constituents of electric currents. They move in the same direction to conduct electricity," Yao added, comparing the movement of free electrons in metals and semiconductors to the flow of water molecules in a stream of water.

The researchers say that new material—which can be bent into almost any shape without breaking, and is 1 millionth the thickness of a single sheet of paper—could help advance the application of spin electronics or spintronics, a new technology that uses the orientation of an electron's spin rather than its charge to encode data. "Our 2-D magnet may enable the formation of ultra-compact spintronic devices to engineer the spins of the electrons," Chen said.

"I believe that the discovery of this new, robust, truly two-dimensional magnet at room temperature is a genuine breakthrough by Jie Yao and his students," said co-author Robert Birgeneau, a faculty senior scientist in Berkeley Lab's Materials Sciences Division and professor of physics at UC Berkeley who co-led the study's magnetic measurements. "In addition to its obvious significance to spintronic devices, this 2-D magnet is fascinating at the atomic level, revealing for the first time how cobalt magnetic atoms interact over 'long' distances" through a complex two-dimensional network, he added.

"Our results are even better than what we expected, which is really exciting. Most of the time in science, experiments can be very challenging," he said. "But when you finally realize something new, it's always very fulfilling."

More information: Rui Chen et al, Tunable room-temperature ferromagnetism in Co-doped two-dimensional van der Waals ZnO, *Nature Communications* (2021). [DOI: 10.1038/s41467-021-24247-w](https://doi.org/10.1038/s41467-021-24247-w)

Provided by Lawrence Berkeley National Laboratory

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