Flexy, flat and functional magnets

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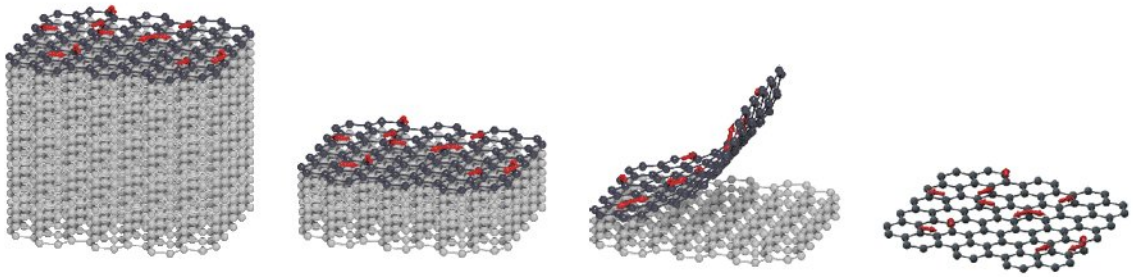


They are formed by ultrathin layers, held together by weak bonds, thus it is possible to control their thickness by simple peeling. The magnetic properties are given by the spin, represented with red arrows. Credit: IBS

In the nanoworld, magnetism has proven to be truly surprising. Magnetic 2-D materials just a few atoms thick could provide a substrate for ever-smaller post-silicon electronics. An international research team led by Park Je-Geun at the Center for Correlated Electron Systems, within the Institute for Basic Science (IBS), has just published a Perspective Review paper in *Nature* presenting the latest achievements and future

potential of 2-D magnetic van der Waals (vdW) materials, which were unknown until six years ago and have recently attracted worldwide attention.

VdW materials are made of piles of ultra-thin layers held together by weak van der Waals bonds. The success of graphene—vdW's star material—stimulated scientists to look for other 2-D crystals with layers that can be changed, added or removed in order to introduce new physical properties, like magnetism.

How do materials become magnetic?

Each electron in a material acts like a tiny compass with its own north and south poles. The orientation of these "compass needles" determines the magnetization. More specifically, magnetization arises from electrons' spin (magnetic moment) and depends on temperature. A ferromagnet, like a standard fridge magnet, acquires its magnetic properties below the magnetic transition temperature—Curie temperature (Tc). When all the magnetic moments are aligned, all "compass needles" point in the same direction. By contrast, other materials are antiferromagnetic, meaning that below the transition temperature—called the Neel temperature (TN)—the "compass needles" point in the opposite direction. For temperatures above Tc or TN,the individual atomic moments are not aligned, and the materials lose their magnetic properties.

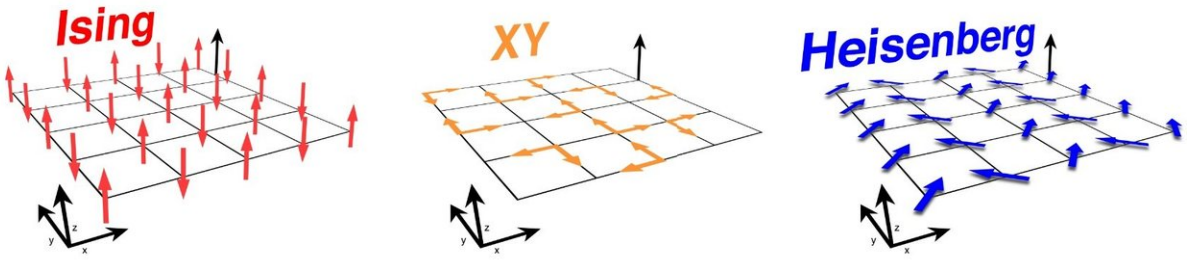
However, the situation can dramatically change upon reducing materials to the 2-D nanometer scale. An ultra-thin slice of a fridge magnet will probably show different features from the whole object. This is because 2-D materials are more sensitive to temperature fluctuations, which can destroy the pattern of well-aligned "compass needles." For example, conventional bulk magnets, such as iron and nickel, have a much lower Tc in 2-D than in 3-D. In other cases, the magnetism in 2-D really

depends on the thickness: Chromium triiodide (CrI3) is ferromagnetic as monolayer, anti-ferromagnetic as bilayer, and again ferromagnetic as trilayer. However, there are other examples, like iron trithiohypophosphate (FePS3), which remarkably keeps its antiferromagnetic ordering intact all the way down to monolayer.

The key for producing 2-D magnetic materials is to tame their spin fluctuations. Two-dimensional materials with a preferred spin direction (magnetic anisotropy) are more likely to be magnetic. Anisotropy can also be introduced artificially by adding defects, magnetic dopants or by playing with the interaction between the electron's spin and the magnetic field generated by the electron's movement around the nucleus. However, these are all technically challenging methods.

Park explains it with an analogy: "It is like supervising a group of restless and misbehaving kids, where each kid represents an atomic compass. You want to line them up, but they would rather play. It is a hard task, as any kindergarten teacher would tell you. You would need to precisely know the movements of each of them in time and space. And to control them, you need to respond right there and then, which is technically very difficult."

Several fundamental questions can be answered thanks to 2-D magnetic vdW materials. In particular, vdW materials are a testbed to find experimental evidence for some mathematical-physical models that still remains unsolved. These models explain the magnetic transition behaviour in relation to the spin. In particular, the Ising model describes spins ("compass needles") constrained to point either up or down, perpendicular to the plane. The XY model allows spins to point at any direction on the plane, and finally, in the Heisenberg model, spins are free to point in any x, y, z direction.



These models differ by the constrains given to the orientation of the electron's spins (arrows). If all spins are aligned in one direction, the material becomes a ferromagnet. Below the magnetic transition temperature, adjacent spins affect each other's behaviour, but as the temperature rises, they move more independently. The Ising model refers to spins with only two directions (z-axis); up or down. In the case of the XY model, the spin follows x- and y- axis on a plane, and in the Heisenberg model, spins take various directions, much like how clock hands point in a number of directions. Credit: IBS

In 2016, IBS scientists of Prof. Park's group found the first experimental proof of the Onsager solution for the Ising model. They found that FePS3's Tc is 118 Kelvin, or minus 155 degrees Celsius, in both 3-D and 2-D. However, the XY and Heisenberg models in 2-D have encountered more experimental barriers, and are still lacking a proof after 50 years.

"The discovery of graphene led me to wonder if I could introduce magnetism to 2-D materials similar to graphene," explains Park. "Physicists have inherited the challenge of studying and explaining the physical properties of the two-dimensional world. In spite of its academic importance and applicability, this field is very much under-explored," he adds.

Scientists are also keen on exploring ways to control and manipulate the magnetic properties of these materials electrically, optically and

mechanically. Their thinness makes them more susceptible to external stimuli. It is a limitation, but can also be a potential. For example, magnetism can also be induced or tuned by strain, or by arranging the overlapping layers in a specific pattern, known as the moiré pattern.

Expected applications of magnetic vdW materials

Although several fundamental questions are still waiting for an answer, controlling and modifying electrons' spins and magnetic structures is expected to lead to several desirable outputs. This *Nature* Perspective Review lists possible research directions for the future.

One of the most sought-after applications is the use of spin to store and encode information. Controlled spins could replace current hard drive platters, and even become the key to quantum computing. In particular, spintronics aims to control electron spin. Two-dimensional materials are good candidates, as they would require less power consumption in comparison with their 3-D counterparts. One interesting hypothesis is to store long-term memory in oriented magnetic poles patterns called skyrmions in magnetic materials.

Potentially, vdW materials could unveil some exotic state of matter, like quantum spin liquids, a hypothetical state of matter characterized by disordered "compass needles" even at extremely low temperatures, and expected to harbor the elusive Majorana fermions, particles that have been theorized, but never observed.

In addition, although superconductivity and magnetism cannot easily be accommodated in the same material, tinkering with spins' order could produce new, unconventional superconductors.

Lastly, although the list of vdW materials has grown very quickly in recent years, less than 10 magnetic vdW materials have been discovered

so far. Engineering more materials, especially materials that can be used at room temperature, is also an important goal of condensed matter physicists.

More information: Kenneth S. Burch et al, Magnetism in two-dimensional van der Waals materials, *Nature* (2018). DOI: 10.1038/s41586-018-0631-z

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