Nanostorage

Devices Enhance Computers in a Big Way

Computers today serve as a jukebox, movie archive and photo album, and must thus provide fast access to ever-larger amounts of data. Scientists at the **Max Planck Institute for Intelligent Systems** in Stuttgart and the Halle-based **Max Planck Institute of Microstructure Physics** are paving the way for magnetic storage materials that make this possible, cleverly taking advantage of the unique laws of the nanoworld.

TEXT **CHRISTIAN MEIER**

Physicist Richard Feynman's vision is quite breathtaking even today: he imagined it would be possible to store the contents of all the books in the world – which Feynman estimated to number 24 million in the late 1950s – in a dust particle that is just barely visible to the naked eye. To do this, however, a digital bit – the smallest storage unit that can record the values zero and one – would have to be squeezed into a space corresponding to the volume of just 100 atoms.

MAGNETIC STORAGE DEVICES ARE REACHING THEIR LIMITS

Perhaps it was this idea that has been spurring on engineers. At any rate, they have been packing more and more data onto storage media, such as hard disks, ever since. Their storage density, or the number of bits per square centimeter, doubles every 18 months. Some 30 years ago, a hard disk could hold around ten megabytes of data; today, they can store 100,000 times this amount. One bit still occupies a few hundred thousand atoms on a terabyte hard disk. If bits and bytes continue to shrink at the current rate, Feynman's dream will come true in around ten years.

But the journey into the nanoworld, where a few hundred atoms store or process information, is becoming more and more troublesome. Magnetic storage media such as hard disks cannot be miniaturized to just any size. Magnetic layers on their surface contain storage cells that each record one bit. Whether the cell constitutes a zero or a one is determined by a cell's magnetization, which results from the sum of the magnetic moments that the individual atoms in the cell carry. Each atom acts as a tiny bar magnet, the direction and strength of which is stipulated by the magnetic moment. The magnetic moments of the atoms align either ferromagnetically or antiferromagnetically – that is, either all parallel or alternately in one direction and then in the opposite direction – to form storage points.

THE NANOWORLD HOLDS MANY SURPRISES

The smaller the storage cells become, the more unstable they become – in other words, the magnetization changes involuntarily by itself solely by virtue of the cells absorbing thermal energy from their surroundings. This means that data is lost over time. In addition, the process of writing data onto hard disks through the effect of magnetic fields has its limitations, because magnetic fields are not really entirely suitable as arbitrarily fine pens.

As engineers continue to shrink storage cells, they venture further and further into the nanoworld, which is full of surprises. The mere fact that something becomes smaller than approximately 100 nanometers often fun-

Photo: M. Kammerer/MPI for Intelligent Systems/NATURE, April 12, 2011

damentally changes its physical and chemical properties. In addition, in this size range, the bizarre laws of quantum physics come into play. These laws sometimes pose problems for electrical engineers, but they also open up opportunities for new storage mechanisms.

A FINE PEN FOR MAGNETIC NANOSTORAGE DEVICES

Basic researchers are thus exploring, for example, new phenomena in magnetic nanostructures – and are coming surprisingly close to more than just Feynman's vision. They also want to achieve particularly high-speed data processing, or they are searching for fundamentally new functions that facilitate, for instance, main memory that, unlike today's RAM memory, remembers data even without electricity – the time-consuming process of booting up the computer would then be a thing of the past.

Experimental and theoretical physicists are working closely together on research into magnetic nanostructures. The latter group includes Ingrid Mertig and Arthur Ernst from the Max Planck Institute of Microstructure Physics in Halle an der Saale. The two scientists are researching how, in the future, data can be written to and read from an increasingly smaller space.

Nano-islands for high storage densities: In two atomic layers of iron applied to a copper substrate, magnetization can be changed with an electric field, which can be focused more sharply than a magnetic one.

Photo: MPI of Microstructure Physics

In conventional technology, a writing head emits magnetic field pulses and thus magnetizes the underlying storage cells. "This technology, however, has been largely exhausted," says Mertig. Magnetic fields cannot be concentrated onto an arbitrarily small surface. If the magnetic bits become too small, the magnetic field affects its neighboring cells when a cell is being written – similar to attempting to fill in a square on graph paper using a thick felt-tip pen: the neighboring squares would invariably also receive a bit of color.

So the Halle-based researchers use electric fields as a particularly fine pen. "These can be focused much more sharply than magnetic fields," explains Ingrid Mertig. The catch: an electric field can't penetrate a metal, as the field induces a charge on the surface of the metal, and this charge then blocks the field. The fine felt tip thus writes, as it were, with an empty filler.

Things look different with an extremely thin metal layer – one that consists of just two layers of atoms, and is thus 100,000 times thinner than a human hair. In such a layer, an electric field can, under certain circumstances, affect the layer's magnetization. Experts call this effect, which Ingrid Mertig and Arthur Ernst have been researching for several years, magnetoelectric coupling.

The effect works, roughly speaking, as follows: A strong electric field displaces the free electrons in the layer – depending on the polarity of the field, it either presses them deeper into the layer or pulls them slightly out of it. This leads to the repulsion between the positively charged atomic cores being weakened or strengthened. Depending on the polarity of the electric field, the two atomic layers thus move a few billionths of a millimeter closer together or further away from one another.

» The bizarre laws of quantum physics sometimes pose problems for electrical engineers, but they also offer them opportunities for new storage mechanisms.

As the researchers in Halle found in their numerous calculations, through the quantum mechanical exchange interaction (see box on page 22), the atomic distance affects whether the double layer adopts the ferromagnetic or the antiferromagnetic state. This sparked an idea: they could use an electric field to change the distances, thus switching the magnetization of the layer from ferromagnetic to antiferromagnetic and vice versa. In this way, a bit could change from zero to one.

STORAGE DENSITY COULD BE INCREASED 400-FOLD

In fact, the theorists in Halle, together with experimentalists at the Karlsruhe Institute of Technology, recently used an electric field to write magnetic information in iron islands measuring just a few nanometers in size. An island consisted of two layers of iron atoms on a copper substrate. The team from Karlsruhe, headed by Wulf Wulfhekel, used a scanning tunneling microscope as the pen. An extremely strong electric field of a billion volts per meter is produced at the tip, which ends in a single atom.

The field switches the iron islands from the ferromagnetic state to antiferromagnetic or vice versa. The researchers read the magnetic state of the island by recording how the current flow from the island into the tip of the scanning tunneling microscope changes with the voltage applied. The resulting current-voltage characteristic is quite different for the two states.

The iron islet consists of only around 300 iron atoms – the researchers are thus coming very close to Feynman's dream. A storage medium based on this technology could store data 400 times more densely than today's data storage devices. Although the iron islands are very tiny, their magnetization remains stable. Arthur Ernst knows the reason from his theoretical calculations: "There's a very high energy barrier between the two magnetic states that can be overcome only with the high electric field." This means that the states themselves have approximately the same energy – like two Alpine valleys of the same depth, separated from one another by a high mountain massif. The system therefore does not change spontaneously from one state to the other, because it wouldn't gain a great deal of energy from it.

In which material is the magnetization strongest? Arthur Ernst, Ingrid Mertig, Sergey Ostanin and Michael Fechner (left to right) investigate which composition of the nano-islands results in the strongest magnetoelectric coupling.

The theoreticians' computer models serve as tools in a kind of virtual laboratory. They use them to calculate, for example, how the magnetoelectric coupling depends on the composition of both the double layer and the substrate. In this way, they find the optimum material combination without carrying out costly experiments in the lab.

"The difference in magnetization between the two states should be as great as possible for industrial application," says Mertig. "We have calculated that an iron-cobalt alloy with 25 percent cobalt provides a large magnetic signal," comments the physicist. At present, the researchers in Halle are working with experimental physicists on testing this prediction. Ingrid Mertig is confident: "The predictive efficiency of our models has proved very high in the past."

Another theoretical physicist at the Halle-based Max Planck Institute of Microstructure Physics goes further than even Feynman dared to dream. According to calculations by Valeri

Photo: MPI of Microstructure Physics – Martin Hölzer

Stepanyuk, it is possible to write a bit in just one single atom. "It is not possible to pack information any more densely; the atom is the fundamental limit for the miniaturization of data storage devices," says Stepanyuk. The magnetic moment of the atom would serve as an information storage device. The up or down direction of these tiny compass needles would determine whether they constituted the zero or one of a bit.

Switching between the two states would be done, as Ingrid Mertig and Arthur Ernst do, using a scanning tunneling microscope. And here again, the distance between atoms decides the orientation of the compass needle. But in Valeri Stepanyuk's case, there are only two atoms: one atom, known as an adatom, that lies alone on a metal substrate and is intended to store the bit, and the atom in which the microscope tip ends.

STORAGE DEVICES HAVE TO PROCESS A LOT OF DATA QUICKLY

As Valeri Stepanyuk's calculations show, the moments of the atom in the tip and those of the adatom are parallel if the two are relatively far apart. If the tip draws closer to the adatom, its moment shifts 180 degrees, so that the moments take on an antiparallel orientation. The basis for this switch mechanism is, as with the magnetoelectric coupling used by Ingrid Mertig's team, the quantum mechanical exchange interaction, though in an indirect form (see box).

"Since we don't need an electric field, the switch process is very energy-saving," says Stepanyuk. His team's computer simulations also show that different materials are suitable for such a single-atom storage device. The researchers selected chromium as the tip, and chromium, manganese, iron and cobalt as adatoms.

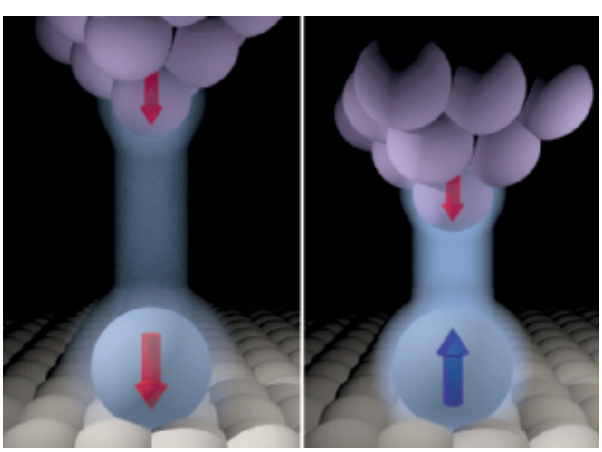
"The computer models can also be adapted to other materials," says Stepanyuk. The stability of the atom bit is also, consistent with his calculations, quite large. And finally, the bit can also be read out, because the electrical resistance between the tip and the adatom

MAGNETIC EFFECT WITHOUT FORCE

Subatomic particles of a certain type, such as protons or electrons, are completely identical – two eggs are true individualists in comparison. This indistinguishability has consequences. The quantum mechanical wave function, which describes the state of a system composed of multiple electrons – as is the case with, for example, an atom or a solid – may not change its value if two electrons change places. Thus, with regard to a particle exchange, it can be either symmetric (it doesn't change at all) or antisymmetric (it changes its sign). The wave function consists of two components: one indicates where the particles are most likely to stay (location component); the other, how the magnetic moments of the particles – that is, their "spin" – are oriented to one another (spin component). Because the wave function of a system composed of electrons must be antisymmetric, a symmetric location component requires an antisymmetric spin component and vice versa. Physicists refer to this as exchange interaction. A symmetric spin wave function corresponds to a parallel orientation of the magnetic moments, an antisymmetric one to the antiparallel orientation.

As the distance between the atoms in a solid increases, a different spatial distribution of the electrons, and an attendant change in the symmetry of the location wave function, may be more energetically favorable. The spin wave function then changes from antisymmetric (antiferromagnetic spin orientation) to symmetric (ferromagnetic) or vice versa.

There is also an indirect exchange interaction, as plays a role in Valeri Stepanyuk's theory. According to this, electrons hop between two atoms (the tip and the adatom) because they then have more room, which reduces the kinetic energy in the system and is therefore preferred. Hopping works better if the magnetic moments of the electrons are oriented parallel to each other. If the tip and the adatom draw closer, then the direct exchange interaction takes effect and an antiparallel orientation of the magnetic moments results.



How the magnetic moment in the atom is oriented on a surface depends on the distance to the tip of a scanning tunneling microscope, due to the indirect exchange interaction.

Graphics: MPI of Microstructure Physics (2)

Physics model in matches: Matthias Kammerer, Gisela Schütz and Hermann Stoll (left to right) illustrate why the magnetic moments in the vortex core form a needle. They found sophisticated methods for quickly turning the needles from top to bottom.

differs measurably according to whether the magnetic moments are oriented parallel or antiparallel to each other.

Up to now, this technology has been only a theoretical possibility. However, an experiment is currently being prepared to check the calculations, Valeri Stepanyuk emphasizes.

Despite all the fascination that Feynman's vision of a particle of dust containing all the knowledge in the world holds: minuteness is not everything. The modern flood of data also requires high-speed storage devices and high-speed access. It's all about "dynamics," as researchers say; in other words, how quickly the switch can be made from zero to one. Writing and reading should require as little power as possible and be technologically manageable in this tiny space and these short periods of time.

Magnetic nanostructures can also score in terms of speed. Basic questions on the high-speed dynamics of magnetic nanostructures are being researched by a team including Hermann Stoll and headed by Gisela Schütz at the Max Planck Institute for Intelligent Systems (formerly the Max Planck Institute for Metals Research) in Stuttgart. For several years, the researchers have been examining the magnetic properties of ferromagnetic wafers made from an alloy of nickel and iron, known as permalloy.

MAGNETIC FIELD PULSES QUICKLY SWITCH VORTEX CORES

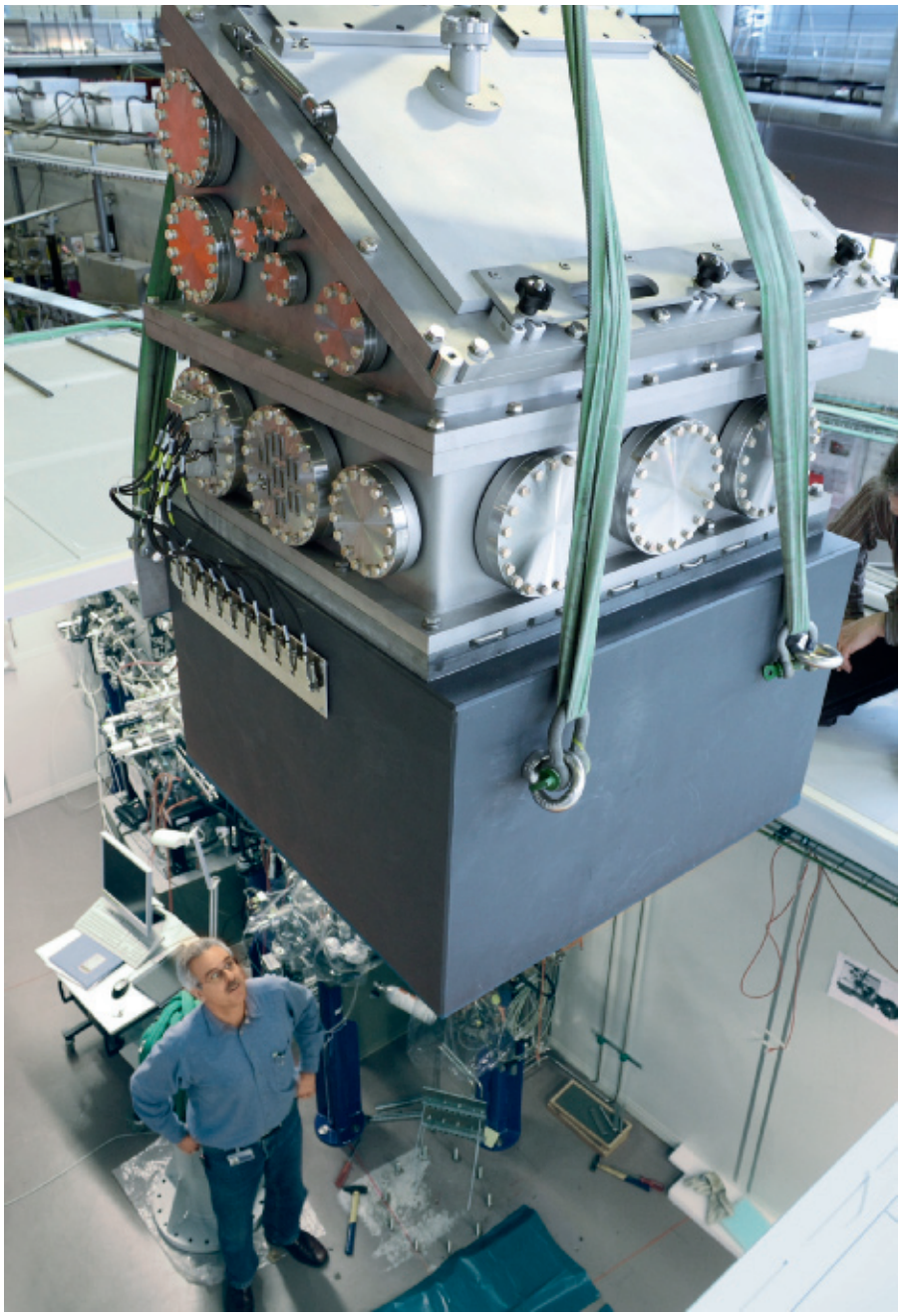
Because of their tile-like form and minuscule dimensions of approximately one thousandth of a millimeter edge length and around 50 nanometers thickness, the permalloy wafers demonstrate a remarkable magnetic phenomenon. The magnetic moments of the metal atoms arrange themselves, not parallel or antiparallel to each other, but rather like a target, forming concentric rings known as vortices.

There is no room for a circle in the center of the vortex structure. How the magnetic moments organize themselves here can be illustrated by trying to lay concentric circles of matches on a table. It is not possible in the center because the matches are too long.

Nevertheless, they can be accommodated by rotating them out of the plane, forming a needle pointing upward. Accordingly, the magnetic moments in the center of the permalloy wafer rotate out of the plane and form a magnetic field needle with a diameter of just about 20 nanometers, a so-called vortex core.

Because the vortex cores can project upward or downward from the two faces of the wafers, they are able, in principle, to store one bit. But there is a problem. "The needle can, indeed, be turned 180 degrees by an external magnetic field," says Hermann Stoll. However, this field must be around 0.5 Tesla, or only about three times weaker than the strongest permanent magnets. The vortex cores therefore seemed unsuitable for data storage devices – they would actually be attractive due to their stability to external magnetic fields, as well as to high temperatures, but they would be quite difficult to switch. >

Photo: Tom Pingel



Using the Maxymus X-ray microscope, which is installed here in Berlin at the Bessy II storage ring, the team headed by Gisela Schütz watches in extreme slow-motion films how the magnetic structure in a material changes on the nanometer scale.

Back in 2006, however, the researchers in Stuttgart found a possibility to specifically switch the otherwise highly stable vortex cores using magnetic field pulses of just 1.5 thousandths of a Tesla. They worked on this with colleagues from Regensburg, Bielefeld, Ghent and Berkeley. The scientists directed an extremely short magnetic field pulse lasting just four nanoseconds – four billionths of a second – onto the wafer. The magnetic field lines of the pulse ran parallel to the wafer instead of vertical.

The result amazed the researchers. These weak magnetic pulses, which need only extremely low power, reliably switched the vortex core. The scientists explained this at the time as follows: roughly speaking, the short magnetic field pulse produces two other magnetic field needles – a vortex-antivortex pair – that are both directed against the originals.

One of the newly formed needles, the antivortex, fuses with the original vortex core, with the two destroying each other. In the end, only the second of the two additional magnetic needles remains and forms a new vortex core – and it points in the opposite direction from the original vortex core. It was this discovery that suggested the use of vortex cores for data storage, because they can now be switched with small and short magnetic field impulses. They also remain very stable to external static magnetic fields.

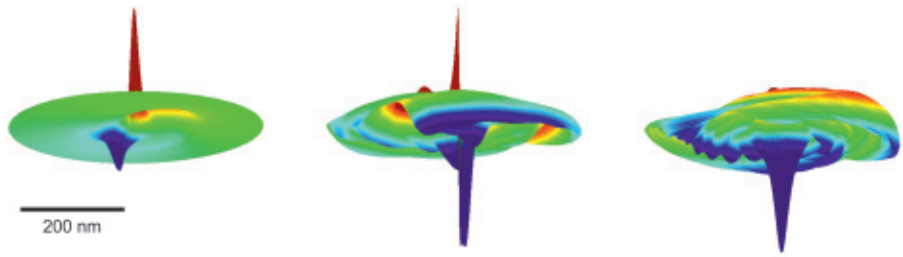
THE SEARCH FOR FASTER SWITCHING PROCESSES

"This discovery was a great stimulus for our research field," says Gisela Schütz. The 2006 publication has since been cited nearly 200 times, and the first experiment and the explanation confirmed in a variety of ways. The Stuttgart-based researchers are now also switching the vortex cores selectively, only from top to bottom or vice versa. For this they use magnetic field pulses that sometimes rotate clockwise and sometimes counterclockwise, thus preventing a pulse from initially turning a vortex core in one direction, but returning it again if the pulse lasts too long.

But that was still not enough for the researchers in Stuttgart. Although the switching times of a few nanoseconds were already in the range of the current fastest storage device systems, the scientists were seeking fundamentally faster switching processes.

Using the Max Planck Society's new Maxymus X-ray microscope at the Bessy II storage ring in Berlin, they

Photo: MPI for Metals Research



The upward- or downward-oriented magnetic needle of a vortex core (left and right simulation) could encode the zero and one of a data bit. Spin waves (center) are created with short magnetic pulses in order to rapidly switch the vortex core. Otherwise, however, it is very stable to static magnetic fields.

were recently able, with colleagues from Regensburg and Ghent, to make another ground-breaking discovery. With this instrument, it is possible to capture images of the magnetic structure of the permalloy wafers with a spatial resolution of 20 nanometers every 30 picoseconds – in other words, to shoot an extreme slow-motion film.

In this way, Matthias Kammerer found, in connection with his doctoral work, a switching mechanism for the cores that lasts just 240 picoseconds, or 0.24 nanoseconds – 20 times faster than was discovered in 2006. And it can be accelerated even further, as the research group determined in theoretical calculations. "It will be possible to push the switching time well below 100 picoseconds," Hermann Stoll believes.

In the new mechanism, a magnetic field pulse leads to spin waves, or wave-like propagation of fluctuations in the magnetization of the material. Ultimately, thanks to these stimuli, two additional magnetic field needles form in the reverse direction to the original vortex core. One of the two new magnetic field needles and the original one then dissolve again literally into nothing.

In the process, the vortex core moves within a radius of less than 20 nanometers, so it essentially doesn't move from the center of the wafer. The vortex structures can thus possibly be reduced to 50 nanometers in diameter if the development of suitable materials progresses further. This makes them competitive in terms of storage density, even if, in principle, they can't be as small as, for instance, the iron islands that Ingrid Mertig is investigating.

The main advantage of the vortex cores, however, is the speed of the switching process, says Gisela Schütz. "Another technologically important aspect is the fact that the vortex cores can be switched with microwave pulses, which can easily be done with today's widely perfected high-frequency technology." The vortex cores can be very precisely addressed with extremely low power through a very fine-meshed grating of crossed tracks in which a magnetic field is generated at each intersection.

NEW PHENOMENA SPAWN UNFORESEEABLE TECHNOLOGY

The researchers have also already solved the problem of reading. A magnetic tunnel contact, a magnetic sensor that is widely used today, is applied over each vortex core. The sensor is just as minute as the underlying storage element and detects the orientation of the vortex core with extreme sensitivity. This creates all the necessary conditions for inserting vortex cores into logic components that process data rapidly and energy-efficiently, believes Hermann Stoll. Or in non-volatile main memories of future computers that don't lose their memory when the computer is switched off.

Mr. Stoll emphasizes, however, that his group is conducting basic research: "First and foremost, our knowledge-oriented experiments and theoretical calculations provide information on the basic dynamics of magnetic nanostructures," he says. "We are seeking new phenomena in minuscule dimensions. These could provide the impetus for completely new technical developments that we can't possibly foresee today."

This was not so very different for Richard Feynman 50 years ago. Even the physics genius himself did not foresee little iron islands in nano-format on which a scanning tunneling microscope writes information, single atoms that become data storage units, and magnetic vortex cores that withstand even an enormous magnetic field, but can be switched by weak magnetic field pulses. Just as researchers today find it difficult to predict the abilities of future computers. ◂

GLOSSARY

Magnetoelectric coupling
With an electric field, this enables the magnetization to be changed in very thin layers. It is based on the fact that the electric field influences the distance between the atoms, which affects the magnetic state of the layer.

Vortex core
In a wafer made of a ferromagnetic material, the magnetic moments of the material arrange themselves, if the edge lengths and thicknesses are not too small, in a circular manner like the rings of a target. At the core of this vortex structure, the magnetic moments rotate upward or downward out of the wafer plane. This vortex core has a diameter of just 10 to 20 nanometers.

X-ray microscope
A microscope that works with X-rays instead of visible light and makes it possible, among other things, to achieve a very high resolution. Using circularly polarized X-rays, it can be used to examine the magnetic order in a sample in great detail.

Graphics: M. Kammerer/MPI for Intelligent Systems/NATURE, April 12, 2011