Magnetic Advantage

Magnetic fields make new thin films better conductors

By ELIZABETH PENNISI

Until four years ago, few researchers paid much attention to the phenomenon of magnetoresistance. Almost 150 years had passed since Lord Kelvin first noticed that magnetic fields cause a slight change in iron's resistance to conducting electricity. But his finding seemed too trivial to warrant much further study.

Then, in 1988, Albert Fert of the University of Paris in Orsay, France, discovered that this minor effect becomes quite major in the right materials. Using a technique called molecular beam epitaxy, Fert made a single crystal "superlattice" by precisely layering iron and chromium. When he put the superlattice in a magnetic field, its resistance dropped by 50 percent at 4.2 kelvins. He called this effect giant magnetoresistance (GMR).

"Everyone was shocked," recalls Chia-Ling Chien, a physicist at Johns Hopkins University in Baltimore. "It was something that had never been seen before."

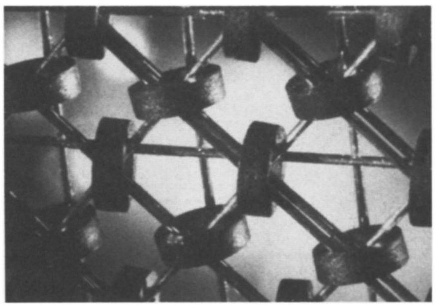
Immediately, Chien and dozens of other scientists around the world began trying to beat Fert's results and to understand this bizarre effect. Their goal: to create materials that, at room temperature, would undergo larger drops in resistance when subjected to much weaker magnetic fields.

"It's the single most active field in magnetics in the world," says Gary A. Prinz, a physicist at the Naval Research Laboratory in Washington, D.C.

Fert's first materials required very strong magnetic fields for their resistance to drop significantly. But newer films require about the same strength as that of a magnet holding a shopping list onto a refrigerator door. And at least one group claims to have made GMR materials sensitive to magnetic fields one-tenth as strong. The drop in resistance is smaller than what Fert observed but still much larger than what scientists could achieve five years ago. "The effects are more than sufficient to do the job," notes Prinz.

The successes in recent months have spurred a highly competitive race to harness this class of materials for electronics or sensors. These advances pave the way for a comeback for magnetic memories in computers. In addition, ever better GMR materials boost the promise of magnetoresistance as a technology for reading stored data from computer disks and tapes. These films may also appear in automobiles, possibly as sensors in self-steering cars (SN: 3/21/92, p.184).

"It has the potential of enormous commercial payoff," says Prinz.


IBM

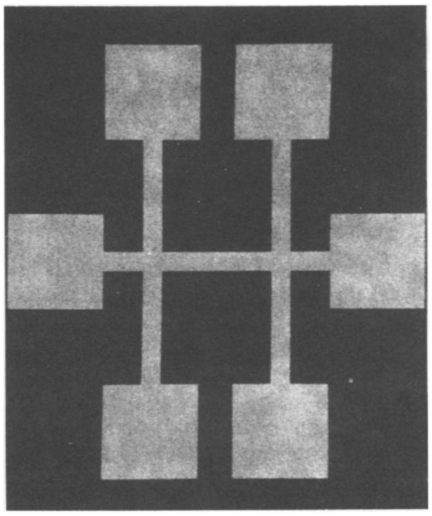
Magnetic memories may make a comeback in computers, not as 1950s ferrite cores (top), but as GMR devices like this prototype (right).

Magnetoresistance arises when magnetic fields help clear the way for electrical current. In any conductor, that current typically encounters obstacles – defects or impurities – that scatter electrons as they move along, creating resistance. While magnetic fields do not affect many of these obstacles, they can overcome scattering caused by magnetic impurities in the conducting material, says Peter M. Levy, a theoretical physicist at New York University. He reviewed progress in giant magnetoresistance in the May 15 SCIENCE.

Those magnetic impurities affect what is called spin-dependent resistance. Each electron possesses an up or down "spin." Impurities magnetized in one direction will deflect up-spin electrons more than down-spin ones, while those magnetized in the opposite direction will scatter down-spin more than up-spin electrons, Levy explains.

In the late 1980s, Peter Grünberg and his colleagues at the Nuclear Research Center-Institute for Solid State Physics in Jülich, Germany, realized that materials scientists could change a material's resistance by refiguring its magnetic properties. The German research team, and later Fert, began to make multilayered films in which alternate layers were magnetized in opposite directions, says Levy. This antiparallel arrangement enhanced resistance, making the material likely to undergo bigger changes in resistivity when subjected to a magnetic field.

They succeeded in making these antiparallel materials by alternating very thin, nonmagnetic spacing layers between thin layers of magnetic material. The influence of one layer's inherent magnetization reached through the spacing layer, causing the next magnetic layer to align its magnetic moments in the opposite direction. This "coupling" resulted in antiparallel magnetization that hampered the free flow of electrons through the film.


Nonvolatile Electronics Inc./Plymouth, Minn.

But then a strong magnetic field causes every layer's magnetization to line up in the direction of the field, creating a low-resistance pathway for electrons of one type of spin. "You have what is essentially a short circuit," says Levy.

Since Fert and Grünberg made those first GMR "short circuits," many other research groups have experimented with a wide range of combinations and internal magnetizations to make new GMR materials. The more they learn, the more puzzling the effect becomes. "There are a large number of unresolved questions," says Stuart S. P. Parkin of the IBM Almaden Research Center in San Jose, Calif. "There's the potential of a lot of new physics that's involved."

At Almaden, Parkin and his colleagues designed a computer-controlled device that enabled them to make 20 kinds of films every three hours. They tried combinations of metals whose atoms arranged in a similar fashion when they formed crystals. First they hit upon a cobalt and ruthenium film that showed a slight GMR. They went on to find even better pairings – for example, cobalt and copper.

After surveying about 100 other combinations, they realized that as they moved from left to right across the periodic table in choosing the spacer- layer element, the degree of coupling varied systematically, says Parkin.

A second group at IBM Almaden, led by Virgil S. Speriosu, came up with a much simpler GMR material. This team sandwiches a nonmagnetic spacing layer between two magnetic layers. By adding a coat of iron-manganese alloy to an outside face of the sandwich, they fix that coated layer's magnetic orientation. They can then study what happens to resistance when they rotate the other layer's magnetic orientation by adjusting the direction of an externally applied magnetic field. In a sense they "spin" the magnetization – hence the name "spin valve" for this type of film.

At the Naval Research Laboratory, Prinz and his colleagues used molecular beam epitaxy to make a variety of layered materials combining copper with cobalt, iron or nickel with chromium, and copper with various alloys, varying the texture of the interface to study its effect on coupling. In other experiments, they replaced an iron layer with different alloys to study the role of free-moving electrons in GMR. "The interfaces are frankly the crucial issue," Prinz concludes.

Unusual experiments at Michigan State University in East Lansing underscore the importance of interfaces and of the thickness of the spacing layers. Rather than study conduction along the length of a thin film, Michigan physicist Peter A. Schroeder and his colleagues monitor current passing straight through the film. Schroeder made multilayered films, each with copper spacing layers of a different thickness. He sandwiched the copper between cobalt layers. "The thickness of the copper layer is very significant; it can cause the magnetoresistance to change by large amounts," he says.

In the July PHYSICAL REVIEW B, Schroeder and his colleagues demonstrate that the interface itself adds to GMR and that the contribution of the interface depends on the orientations of the magnetization in the magnetic layers.

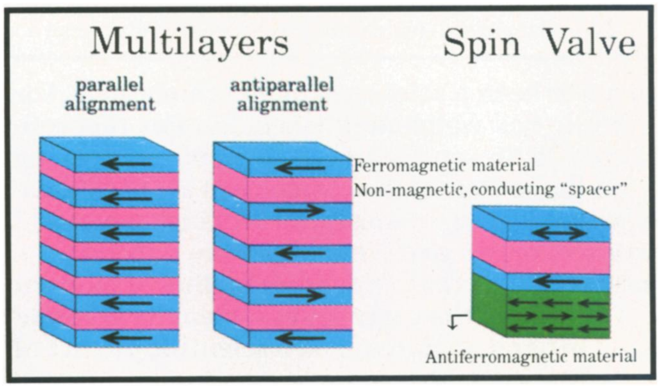
IBM experiments also point to interfaces as key to GMR. In one study, Parkin inserted a thin layer of cobalt at different depths in a GMR film made with copper and a magnetoresistive nickel-iron alloy. "If he put it at the interface, he got a huge amplification of the [GMR] effect," says Levy. Results of another IBM study showed that a layer of iron at the interface between copper and cobalt in a different GMR film greatly dampened the resistance change.

"In both coupling and GMR, the interface plays a crucial role in determining the magnitude of the effects," says Parkin. Thickness variations of only one or two atoms at that interface can make a big difference, he adds. He also finds that the coupling strength increases and decreases periodically as he makes ever thicker spacing layers.

Experiments at the National Institute of Standards and Technology in Gaithersburg, Md., help clarify why these oscillations arise. Physicist Robert J. Celotta and his colleagues used a special electron-microscopy technique to observe how the spacer layer influenced coupling of the magnetic layers to either side. The researchers deposited a wedge of chromium atoms on an iron substrate. Then they coated the chromium with more iron. With their technique, called scanning electron microscopy with polarization analysis, they imaged the direction of magnetization along the iron coat as the thickness of the chromium wedge increased from 1 to 60 layers of atoms.

"It came out to be a very nice checkerboard picture," says Celotta. Once the chromium wedge swelled to about 10 layers, the iron magnetization reversed with each new layer added.

When the researchers examined the magnetization of the chromium itself by leaving off the top iron layer, they were quite surprised. Even though chromium usually shows no magnetization above 311 kelvins (room temperature), Celotta's team did see magnetization in the wedge. They also noticed that the direction of the magnetization reversed with each successive layer of atoms. "The bottom iron layer induces this magnetization pattern in chromium," Celotta says.



IBM/Almaden

In magnetic fields, antiparallel layers become parallel (far left). In spin valve materials, the direction of magnetization (black arrows) becomes fixed in one layer (right).

All of these efforts reinforced the notion that layering – or at least the boundaries between layers – is essential to achieving GMR. Then, in back-to-back reports in the June 22 PHYSICAL REVIEW LETTERS, two independent research groups announced that they had observed GMR in a much different type of material. Chien and two colleagues made a thin copper film that contained very tiny particles of cobalt. And so did a group led by Ami E. Berkowitz, a physicist at the University of California, San Diego.

"They saw that you didn't have to make multilayers at all," says Prinz. "Yet they get the same effect. That's stunning."

In these granular GMR materials, the particles' magnetizations are not antiparallel. "They are helter-skelter," Levy says. Magnetic fields align these random magnetizations, making it easier for electrons to thread their way through. "But the effect won't work unless there's a spatial distribution between the regions that are antiferromagnetically aligned," he adds.

Earlier work by Chien's group on melding incompatible metals into alloys made this new material possible. Chien and his colleagues had discovered that they could make two immiscible metals, such as copper and cobalt, form a homogeneous alloy by depositing vaporized atoms on a cool substrate. The low temperature "quenches" the vapors, tricking the two metals into a delicately stable relationship; heating causes the two to separate.

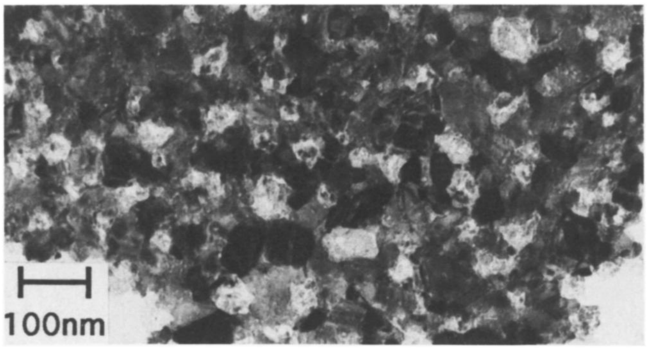
Chien realized he could take advantage of the fragility of this relationship to make a granular material. As he warms the copper-cobalt alloy, small islands of cobalt begin to appear in the copper sea. "By simply changing the temperature, you can change the grain size," he says.

The Hopkins group made a variety of samples with grains up to 20 nanometers across. Their first attempts – for example, a copper-cobalt that exhibited a 9 percent GMR at 5 kelvins – pale in comparison to their most recent material, a cobalt-silver granular film that becomes 80 percent less resistant at low temperatures and 30 percent at room temperature, Chien reports.

Berkowitz, like Chien, has been working to improve upon his group's original granular GMR materials. He finds that the size of magnetic particles in the final film is affected not only by processing temperature but also by the relative concentration of magnetic to nonmagnetic components.

Like the first layered GMR materials, the initial granular GMR films required large magnetic fields to show the drop in resistance. But Berkowitz and Chien think they can lower that field strength to a practical level. "There are a number of approaches we are trying, and they seem to be successful," says Berkowitz. "And there are ways of reducing the [magnetic] field without giving up magnetoresistance."

Once they lower the magnetic field required to obtain GMR, then Berkowitz expects the granular films to surpass the layered ones in their potential for commercial application. Not everyone agrees, but granular films do offer some advantages. "This [GMR] film is infinitely easier to prepare," Berkowitz says. Moreover, these films respond in a more linear way than other magnetoresistive materials to changes in magnetic fields and may emit clearer signals, he says.



Chien/Johns Hopkins

In this granular GMR material, magnetic cobalt particles are embedded in nonmagnetic silver surroundings.

Time will tell whether granular or layered GMR materials will prove tough and economical enough to make it into the marketplace. Already, magnetoresistive materials form the basis of magnetic-stripe readers for automated teller machines and mass-transit fare cards. IBM makes a disk drive read by magnetoresistive heads.

GMR materials should expand the potential of these materials, says Speriosu. A GMR film's stronger signal improves on current magnetoresistive materials by making the signal easier to detect above the random fluctuations in current. "The bigger the resistance change, the better the signal-to-noise ratio," Prinz explains. Thus, engineers can design heads that work faster and can reduce the size of the memory elements, increasing data-storage capacities.

Other scientists want to use GMR materials as nonvolatile memory for computers. Today, memory in most computers resides in semiconductors, which typically need a constant supply of current to keep from forgetting their charges – and their data. Nonvolatile memory lasts even if all power dies.

GMR materials offer many advantages over other nonvolatile memories, which degrade when used. Because GMR films encode bits of data with the direction of their magnetic moments, "you can cycle [them] an infinite number of times," says Prinz. One can also reduce the size of a GMR memory element quite a bit without making it susceptible to failure when temperatures change. Finally, these new materials work very fast. It takes just a few billionths of a second for resistance to drop. "And resistance is very easy to measure," Prinz says.

At the Intermag '92 Conference, held this spring in St. Louis, one company demonstrated a prototype memory device made with a GMR material. A film that combines copper with an undisclosed alloy shows a 6 to 8 percent drop in resistance at room temperature and in weak magnetic fields, says James M. Daughton, who has developed these materials for Nonvolatile Electronics, Inc., in Plymouth, Minn. His group was already looking into using magnetoresistive materials for permanent data storage prior to the discovery of GMR in 1988, he says. But GMR gave the project a big boost.

"I started to work on it instantly," Daughton recalls. "It came along just at the right time for us." □