Heeger. "We have a bit of catching up to do," in achieving full-color and long-life devices, adds May. Although polymers may be lagging at the moment, if they can catch up on performance, May and others believe they will be unbeatable because of their flexibility and the fact that they should cost much less to make than crystalline films made from small molecules, which must be painstakingly grown in a vacuum. Polymer films, by contrast, can be made with lower-tech processing, such as spin-coating—put a drop of polymer solution in the middle of a substrate and spin.

And polymer LEDs are indeed making some headway in performance. At the Materials Research Society conference held in San Francisco last April, for example, Yu presented the latest work on Uniax's polymer devices showing a lifetime of over 10,000 hours at a brightness of 100 cd/m$^2$. Due to patenting concerns, Yu says that he cannot reveal the precise changes that led to the record-breaking lifetimes. He does say, however, that Uniax has been working to improve the contacts between the electrodes and polymers and refine the synthesis of their polymers to reduce the number of defect-causing impurities.

Other groups are also making progress. Emiel Staring's team at Philips Research Laboratories in Eindhoven, the Netherlands, recently announced polymer devices with lifetimes of several thousand hours. Meanwhile May and colleagues at CDT have created devices with modest brightness, but that last at least 7000 hours. Both Uniax and CDT officials say they hope to begin pilot production of devices next year.

Though some companies are pushing ahead with commercialization, they may have a tough time sorting out some of the fine details. Electrodes made from reactive metals like calcium are a particular problem. Such materials are unmatched in their ability to push electrons into organic films, boosting device brightness, but since these metals quickly degrade upon exposure to air or water vapor, commercial devices will have to be sealed tight against the elements. "I'm always concerned with technologies which depend for their life on good encapsulation, which is the case here," says Kmetz. Due to such concerns, Heeger says he expects that first-generation products are likely to be encased in glass. This will make the displays heavy and inflexible, thus losing some of benefits of using organic films. But now that organic light emitters are living longer, most display makers agree that companies now have an incentive to improve their encapsulation schemes. If successful, look out for an organic TV on a wall near you.

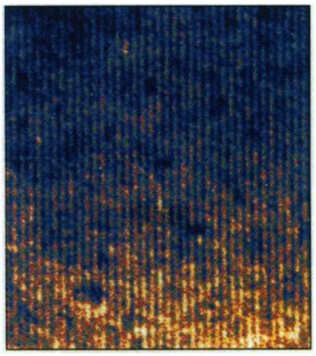
–Robert F. Service

MAGNETORESISTANCE

# Multilayers and Perovskites Rewrite Rules of Resistance

In the 170 years since Georg Ohm identified a fundamental rule of electric current, his eponymous law has become almost as immutable as Newton's law of gravity: In a metallic conductor at normal temperatures, electric current is proportional to the applied voltage and inversely proportional to the metal's resistance. But 10 years ago, Peter Grünberg of the Jülich Research Center in Germany investigated a metallic structure that did not appear to obey Ohm's law. He constructed a sandwich of two iron layers separated by a thin film of chromium and found that at constant voltage he could vary the current through the sandwich simply by applying a magnetic field. The resistance of the structure could be changed with a magnetic field.

This phenomenon initially caused more curiosity than excitement, largely because the effect Grünberg produced was quite small. But 2 years later, when Albert Fert of the University of Paris Sud achieved a 50% change in resistance in a multilayer system of 40 layers of iron alternating with very thin films of chromium, several companies began to take notice. The phenomenon offered tantalizing prospects for applications such as reading heads in hard disk drives and digital videotape recorders: A device whose conductivity is exquisitely sensitive to magnetic changes would be ideally suited to quickly converting magnetically stored information into electrical signals.



Deep freeze. Stripes of charge in manganese perovskite at 95 K.

C.H. CHEN & S.-W. CHEONG/BELL LABS, LUCENT TECHNOLOGIES

These prospects spurred a frenzy of activity in labs around the world, and researchers were soon achieving huge changes in resistance in devices similar to Grünberg's. (Yvan Bryunseraede of the University of Leuven in Belgium holds the current record—a 220% resistance change—in a multilayer of 50 alternating films of iron and chromium, although he had to cool it to 1.5 kelvin.) The phenomenon has gained the title giant magnetoresistance (GMR), and the first GMR devices are "not so far off," says Grünberg. "We hold the basic patent for the application of GMR," he says, "and people at IBM, who have a license, say that around the turn of the century they expect to [have some products] on the market."

And these could be just the forerunners of devices based on an even more pronounced magnetoresistive phenomenon, dubbed colossal magnetoresistance (CMR). This new effect has its roots back in 1950, when two Dutch scientists, G. H. Jonker and J. H. Van Santen, of Philips in Eindhoven, who were studying complex oxide materials called manganese perovskites, noticed that these materials changed their resistance when they were placed in a magnetic field. Their results went largely unnoticed until 1993, however, when several groups—among them Fert's in Paris and teams at AT&T Bell Laboratories in Murray Hill, New Jersey, and the Max Planck Institute for Metals Research in Stuttgart—began working with these materials and soon reported changes in electrical resistance orders of magnitude greater than those achieved in GMR structures. "These materials ... really switch from metal to insulator in a field of a few tesla," says Andrew Millis of Bell Labs (now owned by Lucent Technologies).

Although the resistance changes in CMR materials are extreme, devices based on them may still be some way off because the effect is weaker at higher temperatures and can only be achieved at low temperatures and high magnetic fields. Nevertheless, research on these materials has skyrocketed worldwide, and it has benefited from the intense study of the closely related copper perovskites which were found to exhibit high-temperature superconductivity (HTS) in 1986. "People are using their experience [from HTS research]. This is why this area is evolving very rapidly," says Victor Moshchalkov of University of Leuven.

Many researchers believe that there are still more surprises in store from magnetoresistive materials. "People have not measured the magnetoresistance on many materials yet," notes Sungho Jin of Bell Laboratories, who coined the term CMR. Moshchalkov agrees, citing the unexpected discovery of HTS: "We know that oxides are insulators, and only a complete idiot would look for HTS in oxides. But these complete idiots were right."

**Moment to moment.** The key to GMR lies in the magnetic nature of the metals used in the multiple layers. Each atom in a metal can be viewed as a minute bar magnet: The electrons orbiting the nucleus create a tiny magnetic field known as a magnetic moment. In so-called ferromagnetic materials such as iron, all the magnetic moments of the atoms naturally align themselves in the same direction. But if you bring two layers of iron close together without letting them touch, the magnetic moments in each layer will arrange themselves in opposite directions, just like two compass needles repelling each other. This effect is called "antiferromagnetic coupling." Hence in a multilayer structure of alternate chromium and iron layers, the magnetic moments in each iron layer will point in opposite directions to those in its two neighboring iron layers. Chromium, which is not ferromagnetic, acts as a form of magnetic insulation between the iron layers.

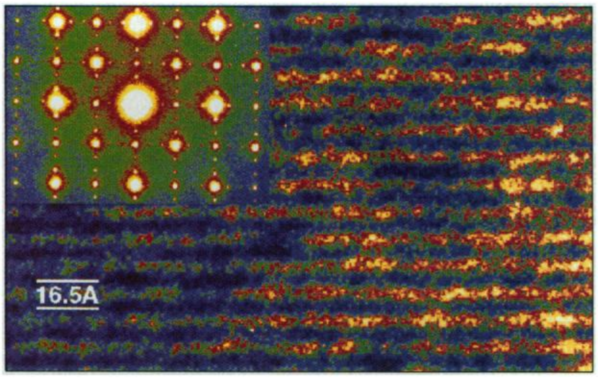
Such a structure makes a poor conductor because conduction electrons themselves have a magnetic moment, and they are more likely to be scattered by an iron atom whose moment is in the opposite direction. So an electron moving through such a multilayer will encounter high-scattering moments in every other iron layer. But apply an external magnetic field strong enough to force all of the magnetic moments in the iron layers to point in the same direction, and this effect disappears; the resistance drops.

The mechanism of CMR is not yet clearly understood, although it is believed to be similar to that of GMR but on a smaller scale. "GMR is a [medium-scale] effect—you have big domains of magnets—and the question is how well an electron wave function can diffuse over hundreds of angstroms," says Millis. "In CMR, everything important as far as we understand it takes place on [the scale of] an atom, and really the question is one of atomic physics."

Conduction electrons move through the material by hopping from manganese atom to manganese atom, and they hop most easily if the magnetic moments of all the manganese atoms are parallel to the moment on the electron. However, the moments of the manganese atoms naturally arrange themselves in random directions. "When they are misaligned, the transfer probability decreases. When you apply a magnetic field it causes alignment, and the conductivity goes up," says Venky Venkatesan of the University of Maryland at College Park.

Although most researchers agree that this alignment is important, it is probably not sufficient to account for the huge resistance changes of CMR. "These magnetic oxides are active dynamic systems with many simultaneous interactions," says Venkatesan.

A possible explanation is related to the concept of lattice distortions, known as phonons, which also play a role in the mechanism of traditional superconductors. Electrons flow easily through a superconductor by linking up in pairs to phonons, which help the electrons overcome their mutual repulsion. These pairs "surf" through the material on the phonon, avoiding collisions and hence experiencing no resistance. In CMR materials, electrons do not form Cooper pairs, but instead they are believed to team up with phonons singly. In contrast to superconductors, the phonons tend to trap or 'localize' the electrons, "and it is the competition between the electron hopping brought about by the magnetic field and phonon localization which is crucial," says Millis. "If you turn off the magnetic field, or raise the temperature, then the electron hopping gets less, which allows the electron-phonon interaction to localize the electrons" and increase resistance.

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**Stars and stripes.** Magnetoresistance in manganese perovskites is still poorly understood.

**Head to head.** While theorists have been trying to figure out the mechanism of magnetoresistance, high-tech companies across the world, including AT&T, Philips, and IBM, have been quick to exploit the phenomenon. The first products to reach the market are expected to be magnetic read-out heads for magnetic storage devices such as digital tapes and computer disks. Current read-out heads are based on a related, but much weaker, effect called anisotropic magnetoresistance, in which a magnetic field causes small changes in direction of the magnetic moments in the layers. Magnetic domains on the tape, passing under the head, cause changes in resistance and hence create an electronic signal. GMR heads, being much more sensitive, would allow smaller domains and faster tape.

Because of the extreme sensitivity of GMR materials to magnetic fields, these new materials will allow the magnetic domains to be made smaller and the tape to be run faster. Reinder Coehoorn of Philips says the company has developed a prototype head for digital tape recorders, based on a GMR multilayer. The prototype has an output signal that is ten times as high as current read-out heads.

From a technical point of view, CMR materials are much more difficult to incorporate into devices because they often operate better at low temperatures and require relatively strong magnetic fields, in the order of a few tesla. "Several tesla is not very strong by the standards of laboratories, but it is very strong by the standards of useful devices," says Millis. Hence current R&D efforts are focused on improving the materials' temperature and field performance. "Everybody wants room temperature and low fields," says Sungho Jin. So far, according to Jin, researchers have had no success in trying to coax the field down by varying the ingredients in the perovskites, incorporating rare earths or transition metals. "We looked at a lot of variations, and they all behave the same way, so far—so it probably will have to be something other than the manganites," Jin says.

But researchers at Bell Labs have taken a different tack: They placed a film of a so-called "soft" ferromagnetic material, such as certain iron oxide compounds—which becomes magnetized by a weak field—alongside a CMR film. Applying a weak field to the ferromagnetic film creates a strong magnetic field in its near vicinity, and this enhances the magnetoresistive response in the CMR film—the Bell team claims a 5900-fold improvement at normal temperature. "This concept is a first step to applications," says Bertram Batlogg of Bell Labs.

Venkatesan reports similar research at the University of Maryland, which has increased the sensitivity to magnetic fields by a factor of 5 to 7. The Maryland researchers are exploiting a phenomenon of superconductors called the Meissner effect, in which the material expels a magnetic field from its own bulk—actually forcing the field lines to go around rather than through it. Hence if you make a ring of superconductor, a magnetic field will be forced outside or into the center of the ring. The researchers are exploiting this "focusing" of the field in the center by putting their CMR material there. "We are using the Meissner effect in HTS materials and have shown that the superconductors can be used as a magnetic lens to amplify an external field, and thereby enhance the sensitivity of the CMR material," says Venkatesan.

Despite the hurdles to overcome with these new materials, being able to play around with resistance is giving researchers a whole new perspective. Says Jin: "Look at Ohm's law, V=IR. With R tunable by orders of magnitude, this can change the whole of electrical engineering, the whole of electronics."

**–Alexander Hellemans**

*Alexander Hellemans is a science writer in Brussels, Belgium.*