

is, what molecular changes are involved—is also an open question.

Whatever its underlying mechanism, synaptic scaling simplifies Hebbian models of learning and memory.

For Hebb's synaptic reinforcement to work, a synapse's history should determine its weight in a neural network. Without synaptic scaling, the location of the dendrite, more so than

its history of use, would determine its weight.

CHARLES DAY

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# Grain Boundary Doping May Improve High-Temperature Superconducting Wire

Superconducting wire is a central part of many of the applications devised for high-temperature superconductors in the 15 years following their discovery. With transition temperatures  $T_c$  above the boiling temperature of liquid nitrogen (77 K), these superconductors have the potential to provide cheap, low-loss wires capable of carrying large currents. The technological realization of this potential has been difficult, however, due in part to the anisotropic character of the ceramic high- $T_c$  materials. Although single crystals of high- $T_c$  superconductors have high critical current densities—the figure of merit in wire applications—polycrystalline wires suffer from significantly reduced current-carrying ability.

Recent work by the group of Jochen Mannhart at the University of Augsburg in Germany is raising hopes for increasing the critical current density of high- $T_c$  wire. Their results on doped superconducting heterostructures suggest a way to improve the weak coupling between the polycrystalline grains while preserving the critical current density within each grain.<sup>1</sup>

## The grain boundary problem

The two high- $T_c$  materials most actively being used for wires are bismuth strontium calcium copper oxide (BSCCO) and yttrium barium copper oxide (YBCO) (see *PHYSICS TODAY*, March 1996, page 48). Both are layered materials, with stronger superconductivity within the  $a$ - $b$  planes of the layers than perpendicular to them (the  $c$  direction). For operation at liquid nitrogen temperatures when a strong magnetic field is present, YBCO wires are preferable to BSCCO wires because of their better ability to pin magnetic flux. The widely pursued approach to making YBCO wire—the so-called coated conductor technique—is to deposit the superconductor onto a tape substrate. Depositing films with the  $c$ -axis nor-

Stacking layers of pure and calcium-doped  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  increases the coupling between the superconducting grains without sacrificing the transition temperature.

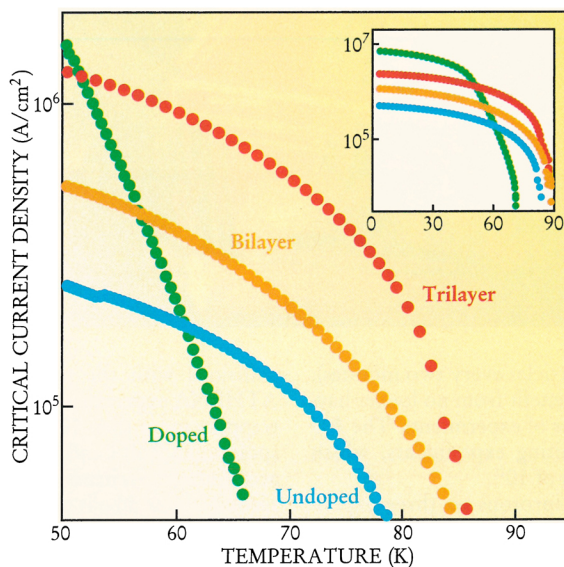


FIGURE 1. CRITICAL CURRENT density, the key parameter in superconducting wire, is plotted here for four bicrystals of yttrium barium copper oxide, each with 24° misalignment in the  $a$ - $b$  plane: undoped  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ , blue; calcium-doped YBCO, green; a bilayer of calcium-doped YBCO on top of undoped YBCO, orange; and a trilayer of undoped YBCO sandwiched between Ca-doped YBCO, red. In the multilayers, calcium appears to diffuse preferentially into the grain boundaries of the undoped YBCO, where it increases the amount of current the superconductor can carry without degrading the superconductor's transition temperature. (Adapted from ref. 1.)

mal to the direction of current flow is fairly straightforward but, unfortunately, not good enough.

The problem is the interfaces between grains in the polycrystalline film. Misalignment of the  $a$  and  $b$  axes by more than a few degrees makes a grain boundary (GB) behave like a

weak link, resembling a Josephson junction and having a critical current that can be significantly below that of the bulk grains.

The weak links at GBs allowed Chang Tsuei (IBM Yorktown) and coworkers to perform their experiments establishing the d-wave symmetry of the high- $T_c$  superconductors (see *PHYSICS TODAY*, January 1996, page 19). But in wires, GBs are unwelcome guests. The microscopic origins of the poor GB behavior is still debated. Possible contributors include the buildup of charge at the boundary, which bends the electronic bands; the squeezing out of oxygen caused by strain fields; structural effects such as scattering off of dislocations; and the d-wave symmetry.

## Calcium to the rescue

It's been known since the early days of YBCO that doping with calcium is one way of adding more hole charge carriers to the material. Divalent calcium is roughly the same size as trivalent yttrium and so readily takes its place within the crystal structure. If a deficiency of holes contributes to the poor GB coupling, as many believe, then if one could get calcium into the GBs, the critical current might be improved.

The Augsburg group examined this possibility<sup>2</sup> in 1999. They worked with a model system of YBCO grown on a substrate of strontium titanate. The  $\text{SrTiO}_3$  was bicrystalline, with the axes of the grains on its two halves misaligned by 24°. Because YBCO grows epitaxially on the substrate, this GB angle was maintained between the grains of the superconducting film.

After doping the YBCO with 30% Ca, the researchers indeed observed a significant increase in the critical current density of the GB—by as much as an order of magnitude at 4 K. But this improvement came at a price: With so much Ca in the material, the  $T_c$  of the superconducting grains fell below 80 K, down from 93 K for the best YBCO

## Antiproton Research Resumes at CERN

Experiments designed to probe differences between matter and antimatter using low-energy antiprotons have been on hold since CERN shut down its Low-Energy Antiproton Ring (LEAR) in December 1996. But the progress made at LEAR motivated the construction at CERN of a \$5 million new facility, the Antiproton Decelerator (AD) (see *PHYSICS TODAY*, March 1996, page 17; November 1996, page 9; and May 1997, page 19). The photo shows the dipole (red) and quadrupole (blue) magnets in a section of the new ring. Antiprotons enter from the transfer line on the right.

Based on LEAR's refurbished antiproton collector, the AD costs only one-tenth as much as LEAR to run. The machine stores only about one percent of the antiprotons that LEAR held, but it sends them out at a rate sufficient for the antiproton experiments (currently in pulses of roughly  $10^7$  particles every two minutes). The antimatter experiments greatly benefit from no longer having to share the beam with other types of experiments. The AD sends 5-MeV antiprotons to the waiting experiments, which must reduce these energies by factors of  $10^{10}$ .

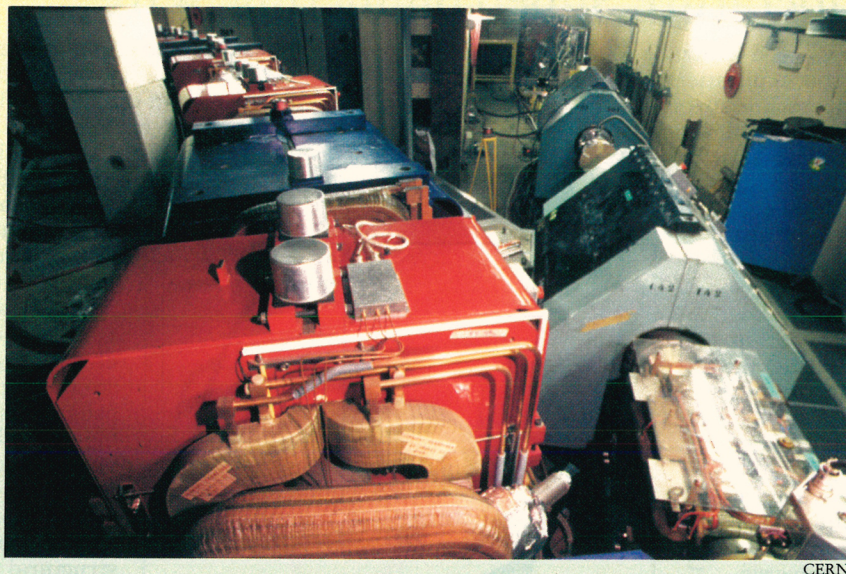
The AD has been supplying antiprotons to three experiments since July. The goal of two experiments, ATRAP and ATHENA, is to form and study atoms of antihydrogen (in which a positron orbits an antiproton). The ATRAP experiment evolved from the TRAP experiment at LEAR, which developed many techniques for trapping and cooling antiprotons. ATRAP is designed to confine both antiprotons and positrons in the same, relatively small, trap (with a radius of 1.2 cm). The ATHENA experiment, built from scratch for the AD, features separate, larger traps for the oppositely charged particles. Each team plans eventually to nudge together the separate

collections of antiprotons and positrons to form antihydrogen atoms. The third experimental collaboration, ASACUSA, is continuing measurements begun at LEAR of the spectral lines of helium atoms in which an antiproton has replaced an orbital electron; the group hopes to determine accurately such properties of the antiproton as its mass and magnetic moment.

Initial reports from the AD are very positive. Speaking for the ATRAP team, Gerald Gabrielse of Harvard University reported that, by late August, he and his colleagues had accumulated nearly 0.1 million antiprotons at 4.2 K in the course of an hour and had simultaneously cooled more than 2 million positrons, also to 4.2 K—the coldest collection of positrons so far assembled. They have seen evidence that the antiprotons are being cooled by

collisions with the positrons stored in the same trap. The ATHENA experimenters have also cooled antiprotons to 4.2 K, trapping more than 10 000 per shot, according to collaboration spokesman Rolf Landua of CERN. At the same time, they have accumulated positrons at the high rate of about one million per second; a next step is to cool the positrons to liquid helium temperatures by transferring them to a cryogenic chamber. Despite the tough challenges that still lie ahead, experimenters with the antihydrogen teams dream of success by year's end. Meanwhile, the ASACUSA collaboration, according to spokesman Ryugo Hayano of the University of Tokyo, is getting two to three times better resolution with the AD, thanks both to the new machine and to improvements in their apparatus. Already team members have seen a new resonance in antiprotonic helium, and they hope to improve the value of the antiprotonic Rydberg constant determined at LEAR.

**BARBARA GOSS LEVI**



CERN

superconductors. At liquid nitrogen temperatures, the decreased  $T_c$  essentially canceled the gains from the improved intergrain coupling.

Recently, however, the Augsburg group has found a potential way to circumvent this drawback, doping only the GBs to achieve good GB coupling while maintaining a high  $T_c$  within the grains. Again using a test system with a 24° GB, the researchers deposited a bilayer with undoped YBCO capped by a thin layer of 30% Ca-doped YBCO.<sup>1</sup> Because of its low  $T_c$ , this top layer doesn't significantly contribute to the current flow through the film at 77 K, but it does provide a source for Ca that can migrate down

into the undoped layers. "We expected that calcium would diffuse into the grain boundaries much more than into the bulk," explains Mannhart. "It appears to have really worked."

Figure 1 shows the critical current densities measured as a function of temperature for undoped, doped, and multilayer YBCO bicrystals, all with 24° GB angles. The multilayer combinations of undoped and Ca-doped YBCO successfully demonstrate the desired result: The  $T_c$  remains high, and yet the critical current density across the GB is significantly enhanced—by more than a factor of six in some doped-undoped trilayers. An increase by more

than a factor of two is typical in bilayers, which may be the more practical structure for commercial wire applications.

No special annealing was performed on the bilayer and trilayer samples; the time spent at high temperatures during the deposition process appears to be sufficient for the diffusion of Ca into the GBs. Mannhart notes, though, that the experimenters have yet to measure the actual amount of Ca that ended up at the GBs of the undoped layer.

### The next step

Still unanswered is the important question of whether the results seen

in Augsburg for large GB angles will carry over to the lower angles more typically found in coated-conductor wire. The best tape substrates for the wire have their own grains aligned to within 8–10°. Yet even at angles as small as 4°, GBs hinder current flow and decrease the current-carrying ability of polycrystalline YBCO wires—as imaged magneto-optically by David Larbalestier and coworkers at the University of Wisconsin<sup>3</sup>—so a method of healing the GB weak links could have significant payoff.

The Wisconsin experimenters have examined the effect of Ca doping on small-angle GBs,<sup>4</sup> looking at uniformly Ca-doped YBCO bicrystals with GB angles of 5° and 7°. Although they, too, find a decrease in  $T_c$ , the researchers observe clear benefits from 30% Ca doping, including a 30% increase in the GB critical current density at 44 K and better behavior at high magnetic field—an important issue in many potential power applications of high- $T_c$  superconductors.

The natural next step, therefore, is to examine samples of Ca-doped bilayers and other multilayers of YBCO with low-angle GBs. There could be a substantial impact on the high- $T_c$  wire community if such Ca-doped multilayers also showed improved critical current densities. Such an increase could reduce the price of high- $T_c$  superconducting wire significantly. “Unless we can do this,” says Paul Grant of the Electric Power Research Institute, “the high price will mean only niche power applications for HTS.” Mannhart and Larbalestier are both optimistic that the benefits of Ca-doped multilayers observed at high GB angles will be duplicated at low angles.

**RICHARD FITZGERALD**

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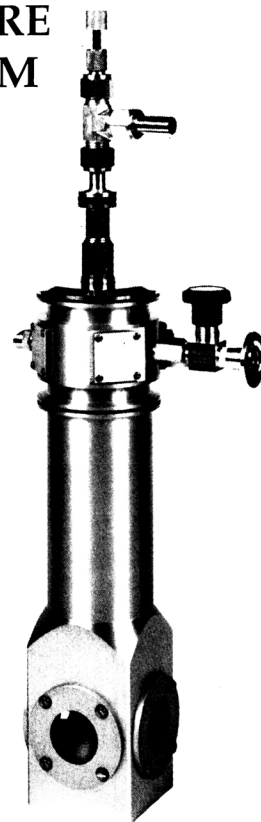
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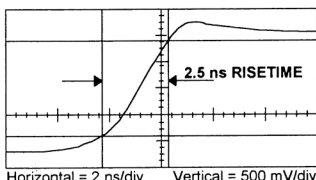
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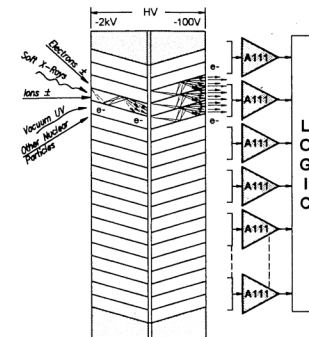
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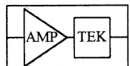
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