form a tightly packed surface—have enormous surface areas in relation to volume: as high as 1000 square meters per gram. That puts them in the same range as carbon black, which forms the standard in high-surface-area materials and is a component of many commercially important heterogeneous catalysts. The combination of high surface area and high solubility could make these polymers useful as catalyst carriers. One thing that makes the prospect appealing is that the dendrimers could be recovered from a reaction mixture by simple extraction or filtration techniques.

Being able to control the architecture of a polymer's surface certainly opens the door to some sophisticated chemistry.

—JEAN FRÉCHET

Alternately, it is possible to make insoluble networks from dendrimers. Webster at DuPont and Tomalia have made thin films of cross-linked dendrimers. Some show potential as catalyst carriers; others might ultimately be used as membranes for separating gases, isotopes, and even biological molecules such as enzymes and other proteins. "Since we can vary the size of the dendrimers and the space between them, we can make filters with very tightly defined pores," says Tomalia.

The main stumbling block to most of these applications is that large-scale synthetic methods remain to be developed. Webster says that current methods of building these molecules from the core produce only small quantities of precisely defined dendrimers. It is possible to make large amounts of starburst dendrimers, but they are less than homogeneous in molecular weight then, since the reactions' conditions are not controlled as carefully, though Tomalia claims that researchers at MMI have just developed a new "kilogram-scale" process that achieves the same homogeneity as previous small-scale techniques.

Even the less-than-homogeneous dendrimer preparations, however, show promise for applications. Fréchet has made dendrimer mixtures that, when added to traditional polymers of similar composition, produce coatings of extraordinary strength and durability. "This, I believe, is where the biggest impact will be in the near future," says Fréchet. Success here, he says, should then produce further advances in more demanding applications, such as drug delivery or membrane separations.

Those demanding applications will require progress in large-scale synthesis, and it is possible that a completely different approach could overcome the problem of scale. Craig J. Hawker, formerly of Fréchet's lab and now at the University of Queensland in Brisbane, Australia, has worked out what those in the field call a "convergent" growth strategy, which starts at the periphery and works back to the core. In this way, it is possible to make dendrimers that have different functional groups covering well-defined regions of the molecule's surface.

Having the ability to make dendrimers with polyfunctional surfaces, says Tomalia, opens up whole new areas for investigation. One application would be to attach tissue-targeting antibodies to one part of the dendrimer and drug molecules to another part. In the same vein, Fréchet believes it should be possible to create artificial catalysts in which the reactants are held on different parts of the molecule and then brought together by a change in pH or solvent.

It might even be feasible to achieve energy storage using a dendrimer that stores opposite charges on different parts of the same molecule. "It's hard to predict what we'll be able to accomplish," says Fréchet, with understandable enthusiasm. He and Tomalia and a handful of researchers around the world are onto a field in its infancy. "We've only just begun making these compounds," Fréchet says enthusiastically, "but being able to control the architecture of a polymer's surface certainly opens the door to some sophisticated chemistry." ■ JOE ALPER

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ADDITIONAL READING

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"Photophysical Investigation of Starburst Dendrimers and Their Interactions with Anionic and Cationic Surfactants." Gabriella Caminati, Nicholas J. Turro, and Donald Tomalia. *J. American Chemical Soc.*, vol. 112, 8515-8522, 1990.

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"Spiral Forest" May

When high-temperature superconductors (HTS) were first discovered more than 4 years ago, a vast new range of superconducting materials appeared to be on the horizon. But in fact only one form of these celebrity materials is currently on the fast track toward real applications: superthin films. The reason: Thin films can carry far more current than bulkier superconducting structures such as wires. That ability may ultimately lead to use of films in faster communications systems, electronic components, sensors for tracking brain activity, and a host of other applications.

But the exact physical properties that enable high-temperature superconductor thin films to carry high currents remain "a bit of a mystery," according to Praveen Chaudhari, a materials scientist at the IBM T. J. Watson Research Center in Yorktown Heights, New York, who was among the first to recognize their enhanced conductivity. Now two teams—one at Los Alamos National Laboratory and one at IBM in Switzerland—may have turned up an important clue to the mystery.

Using scanning tunneling microscopes (STM) and atomic force microscopes (AFM)—tools designed for imaging atomic and molecular landscapes—the teams have discovered unsuspected forests of spiraling grains decorating the films' surfaces. Those tantalizing spiral forests aren't just beautiful artifacts. On the contrary, they may be the defects in the material's crystalline structure that researchers have theorized are at the basis of the current-carrying abilities of thin films, but which have remained undetected. That kind of insight can only hasten the shift of HTS thin films from technology in the works to technology for sale.

Ian Raistrick of the Los Alamos National Laboratory first reported his group's findings on 18 March in Cincinnati at the spring meeting of the American Physical Society (APS). A paper by his group appears on page 1587 of this issue of *Science*. The same evening, during an invited talk, J. Georg Bednorz of IBM Research Division in Zurich, who with K. Alex Müller in 1986 triggered the worldwide research firestorm in HTS materials, briefly described nearly identical observations. His team's work appears in the current issue of *Nature*.

Boths teams focused on thin films of yttrium-barium-copper-oxide, the most widely studied high-temperature superconducting material. Rather than growing layer by layer as many researchers have assumed,

Hold Clue to Thin-Film Superconductivity

the STM and AFM images harvested by Raistrick's coauthor Marilyn Hawley suggest that HTS films actually begin as individual islands that grow together to form a grainy film. Atop each circular or square grain that results from this island growth is a spiraling terrace, its curvature tightening and its altitude rising by 1.2-nm with each revolution. "Our paper is more or less identical," remarks Dario Anselmetti of the Zurich team, though his group reported only STM images.

The Los Alamos team's films were grown by coauthor Robert Houlton in a vacuum chamber using a technique called RF magnetron sputtering. Strong radio waves ionize gas molecules, which smash into a pressed disk containing the correct proportion of atomic ingredients. The atomic debris reassembles in film form onto a heated substrate nearby. A chaser of oxygen brings the films' atomic composition in line with the $YBa_2Cu_3O_7$ formula. The Zurich team grew its films by a slightly different sputtering technique.

The outcome of this process—particularly in relation to the shape and size of the grains—depends on how the films are prepared, Raistrick notes. Grains of films grown on magnesium oxide, for example, have a rectangular shape; those grown on strontium titanate are larger and more circular. The Zurich team reported films grown only on strontium titanate. Films made from atoms liberated from laser-blasted disks of HTS material show far fewer of the spiral structures than RF-magnetron sputtered films.

Chaudhari confesses to being impressed by what he calls the "beautiful pictures" from the Zurich team. But he's more interested in the roles that the grains and spirals might play in high conductivity—especially the possibility that the spirals might be the missing crystalline defects. Such defects have been sought for some time by researchers, who realize that crystalline perfection is a drag for HTS materials, especially in the presence of magnetic fields. Magnetic fields penetrate so-called type II superconductors (which include all HTS materials) in the form of flux lines. If the flux lines aren't somehow immobilized, electrical current coursing through the superconductor pushes the flux lines around, dissipating energy—and spelling the end of the superconductive state. Microstructural defects defend against this phenomenon by pinning the flux lines in place.

Materials scientists have known that those defensive defects come in many forms. These include "point defects," such as oxygen atoms missing from a lattice site; stacking faults, in which adjacent layers fail to align precisely; and larger-scale defects such as boundaries between crystal grains. But even with that catalog it has not been clear what defects are doing the pinning, says Robert B. van Dover of AT&T Bell Laboratories in Murray Hill, New Jersey.

One problem is that the number of defects researchers do find in a given area of HTS thin film is too small to account for the high currents the films can carry. The defect density suggested by the new observations might just fill the gap. "That kind of defect density will give rise to critical currents of the kind we observe," Chaudhari says. But before that connection can be made with confidence, he says, "similar experiments need to be done to see if these structures are present in other films," not just ones made of $YBa_2Cu_3O_7$.

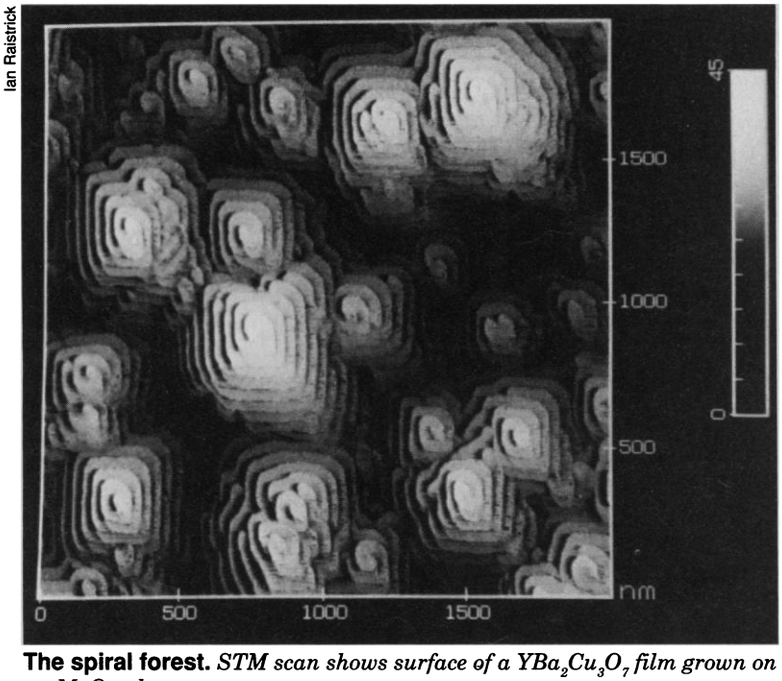
But if these particular defects are so critical for thin films, why haven't they been seen before? After all, plenty of materials scientists have had high quality HTS films for a few years and STMs for longer.

Hawley has no trouble coming up with reasons. For one, in humid settings the films rapidly acquire a nonconducting top layer. That layer blinds an STM and blocks an AFM from directly probing the film's surface. Trying to dodge this problem by imaging the films in a high vacuum, Hawley continues, turns the structure into a moving target for an STM, since oxygen atoms leach out of the films. Finally, she notes, researchers have assumed that features on the films' surfaces are less important than those in their underlying bulk. As a result of this combination of factors, she suspects, many researchers have either tried and failed to image HTS films with an STM or simply haven't bothered at all.

Jerome Beery, who helped to characterize the films at Los Alamos but since has left to run his own technology transfer firm, adds reasons of his own. Most STM researchers scan microscapes far smaller than the several thousand angstrom range typical of the grains. Many scientists may have been missing the enchanting spiral forest because they've been dwelling, say, at one relatively flat terrace of a single spiral tree. Also, most teams look at the thin films with electron microscopes. Since these tools have poor depth perception, Beery notes, what appear as 1.2 nm steps using an STM or AFM look almost flat.

STM experts with friends working on HTS thin films are bound to get busy now that two research teams have shown how revealing STM tours of the films can be. "I used to have a hard time getting people to give me films even just to look at," Hawley recalls. Now she's working long hours to keep up with the flood of thin films pouring in from her colleagues. ■ IVAN AMATO

Ian Raistrick



The spiral forest. *STM scan shows surface of a $YBa_2Cu_3O_7$ film grown on an MgO substrate.*