Superconductor Flux Pinning and Grain Boundary Control
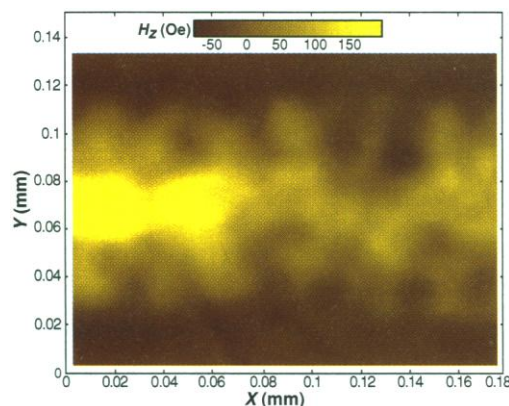
David Larbalestier

Ten years ago in November, an innocuously entitled paper about superconductivity at record-breaking temperatures was published in *Zeitschrift für Physik* (1). Although it took a few months for the field to appreciate the enormous value of Bednorz's and Müller's discovery, predictions of a new superconducting age based on the high-temperature superconductors (HTS) (1, 2) were rampant by mid-1987. A National Academy of Sciences report (3), suggestions to make the superconducting super collider from HTS magnets, proposals to entirely revamp the nation's power grid, and a special Presidential Conference on High Temperature Superconductivity (4) all stimulated the sense that a new materials age might be at hand.

Reality was rather different. The layered, perovskite cuprates were all anisotropic, oxygen-sensitive ceramics, difficult to prepare in controlled form and particularly poor at carrying current, unless made as single crystals. The reason was that in its easily prepared polycrystalline form, virtually all high-angle grain boundaries blocked the current. The problem lay in the very short, nanometer-scale coherence lengths (the distance over which the two electrons in the Cooper pair can bond) of the cuprates.

So stark was the problem that there were no reasonable prospects for wires of HTS until 1989, when to great surprise it was shown (5) that partially melting the Bi-Sr-Ca-Cu-O (BSCCO) inside a silver sheath could lead to high critical-current densities (J_c). This was the crucial result that let dreams of large-scale applications take off. The challenge of the last few years has been to carefully unravel the means by which the very high J_c values found within grains of HTS at low temperatures can be realized in polycrystalline conductor forms suitable for a technology capable of operating at temperatures well above those of the low-temperature superconductors (LTSs), preferably at liquid nitrogen temperatures.

From a technological point of view, the discovery of a new superconductor with a high transition temperature (T_c) is only the first step leading to applications. A prerequisite of any application is that the wires

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Magneto-optical image of the trapped magnetic flux in a 1-μm-thick YBCO film made by laser ablation on an IBAD-oriented YSZ layer deposited on polycrystalline Hastelloy. Brighter regions correspond to higher values of the z-axis flux component H_z. The image was obtained at 77 K after field cooling the sample at 40 mT and then reducing the field to zero. The nonuniform flux distribution directly shows the percolative nature of the current flow. The calculated local critical-current densities vary from 1×10^6 to 2×10^6 A/cm² on the left side of the image, and from 0.5×10^6 to 1.5×10^6 A/cm² on the right. [Sample made by Foltyn and Arendt at LANL and image by Pashitski and Polyanskii at the University of Wisconsin]

achieve a J_c of 10^5 A/cm² or more. The basic physics poses no problem because a high T_c requires a high superconducting condensation energy ($^1/_2\mu_0 H_c^2$ J/m³), where $\mu_0 H_c$ is the critical field, about 1 T for the best HTS materials such as yttrium-barium copper oxide (YBCO) and BSCCO. A 1-T critical field yields a depairing current density (J_d) of ~10^8 A/cm², at least three orders of magnitude larger than is required to support applications. J_d is not a technically realizable current density in wires because J_d flows only at the surface and around the vortices that penetrate superconductors immersed in strong fields.

To achieve high transport current densities, we must pin the vortices by adding suitable defects to the superconductor so that a bulk current can flow through the whole superconductor. This bulk current is controlled by flux pinning, thus defining a current density J_{fp}. J_{fp} can achieve ~0.1 J_d in the low-temperature limit, ~10^7 A/cm², still two orders of magnitude greater than needed. If HTS were LTS, the story would be almost over. The frustration and special challenge of HTS materials is that thermal activation, allied to the very short coherence lengths

and strongly anisotropic properties, means that useful current densities disappear well below the critical temperature. Thus, two major problems have stood in the way of applications of HTS: the grain boundary problem mentioned above and the thermal activation problem. Two recent papers in *Science*, one by Yang and Lieber (6) and one by Norton *et al.* on p. 755 of this issue (7), attack these two problems. Their results illustrate the materials advances possible that can make HTS truly attractive to large-scale users.

The work on flux pinning (6) shows that the useful field and temperature range of the BSCCO-2212 compound can be strongly increased by addition of nanometer-scale rods of the chemically compatible compound MgO. The proof of principle for this technique was first developed by researchers firing heavy ions at HTS, creating nanometer tracks that pinned vortices well (8). A later variant that made use of high-energy protons to fission Bi within the BSCCO compound also worked very well (9), but both methods suffer from the problem of easy translation to the industrial scale. What has been lacking until now is a feasible chemical method of achieving the same effect. Yang and Lieber (6) now show that such a method is in principle possible. Their advance addresses ways to increase J_{fp}, extending the field range over which desired properties can be obtained at high temperatures. The challenge now is to find ways to incorporate chemical pinning centers in the BSCCO compounds in ways compatible with tape fabrication, as recently shown also by Parrell *et al.* (10).

The second problem is to get the current from one grain to another so that it percolates throughout the whole network (11). BSCCO grains tend to self-organize because of the micaceous nature of their double Bi-O layer, but YBCO requires special treatment. High overall J_c can be obtained if biaxial texture is developed so that only low-angle grain boundaries are found. Until now the preferred, conductor-relevant method was ion beam–assisted deposition (IBAD), in which a single–crystal substrate layer for the YBCO was laid down onto a continuous polycrystalline metal tape. IBAD was used to texture YSZ (Y_2O_3-stabilized ZrO_2). Work by Iijima *et al.* (12) and later by groups at LANL (13) showed that this method could yield spectacular success: overall J_c values in the superconductor of 10^6 A/cm² could be attained in liquid nitrogen. Drawbacks to the IBAD process are that it is very slow and that scale-up to long lengths requires large investments in vacuum-process equipment. Now a new realization by groups at Oak Ridge (7)

shows that the IBAD process is not essential and that the textured substrate on which high-J_c YBCO can be laid down can also be prepared by common rolling methods. The prospects for the new techniques are illustrated by the magneto-optical image shown in the figure. Even in a rather well-aligned YBCO tape with a J_c of 5×10^5 A/cm^2, the current is percolating from point to point, thus indicating that we are still far from achieving the true potential of these techniques.

What will be the industrial impact of these two advances? Much depends on translating the science of small samples into conductor-relevant prototypes as explained in a recent U.S. Department of Energy–sponsored report on power applications of

superconductivity (15). Conductors must be electrically continuous, otherwise there can be no applications. BSCCO conductors have made great strides recently as the materials science of the current-limiting mechanisms and its fabrication have become better understood (14). Real conductors must be strong, economical, manufacturable in long lengths, and have high overall J_c values. Here, "overall" means that all of the space required to make the conductor must be counted when the critical current is normalized by the conductor cross section. YBCO has undoubted advantages over BSCCO for use at liquid nitrogen temperatures in magnetic fields of more than about half a tesla. The exciting prospect for those working on applications of high-temperature superconductors is that excellent first-generation conductors of BSCCO are now available, and potential second-generation conductors with strongly improved prospects are in view. All in all, this is a very promising state for a field, not yet 10 years old, that 7 years ago seemed almost stillborn.

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Retroelements in Genome Organization

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Eukaryotic genomes are riddled with genetic freeloaders—transposable pieces of DNA that require host cell functions to replicate and proliferate. Transposition poses a potential threat to the host because integration into new sites in the genome can result in deleterious mutations. Logic dictates that there should be an upper limit to the level of transposition that genomes can endure. It is therefore quite surprising to discover, as reported in this issue of Science (1), the magnitude of transposable elements in the genome of maize. Regions between maize genes are packed with transposable elements inserted within transposable elements, which together make up more than 50% of the two billion base pairs (bp) that constitute this plant's nuclear DNA.

The predominant type of transposable element in maize is the retroelement, which replicates through an RNA intermediate by reverse transcription. Particularly prevalent are two classes of retrovirus-like retrotransposons, the so-called Ty1/copia and

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Ty3/gypsy elements. Retrotransposons are particularly important in shaping plant genomes: Ty1/copia group retrotransposons are found in species throughout the plant kingdom (2), and many plant gene sequences in the DNA databases have adjacent retrotransposon insertions (3). In some cases, these insertions are located in the promoters of plant genes and contribute sequences important for promoter function.

By analyzing a contiguous stretch of plant genomic DNA, SanMiguel et al. reveal that earlier studies had uncovered only the tip of the plant retroelement iceberg. Large blocks of retroelements (greater than 50 kb) were found between single-copy gene sequences in a 280-kb region encompassing the maize adh1 gene. These blocks are made up of at least 10 diverse retroelement families with varying numbers of copies. The five most abundant families alone make up about 25% of the maize genome. The presence of multiple low–copy number families further indicates that many hundreds, if not thousands, of distinct retroelement families exist in maize—an unprecedented wealth of retrotransposon diversity in the genome of a single organism.

Retrotransposons add considerable bulk to the maize genome. This principle may extend to other plants and may account for the remarkable range of sizes observed for plant genomes, from 10^8 bp for Arabidopsis thaliana to over 10^{11} bp for some species of lily. Although Arabidopsis has more than 20 characterized retroelement families, most are present at one to five copies per genome, consistent with the notable lack of interspersed repeats in this plant's nuclear DNA (4). The genomes of many agronomically important grasses are largely colinear yet vary extensively in size (5); for example, the maize genome is 3.5 times as large as that of
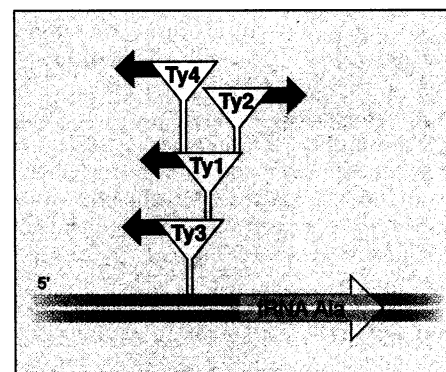
A retrotransposon landing pad. Retrotransposons within retrotransposons are typically found upstream of tRNA genes in S. cerevisiae, as shown by this region 5′ of an alanine tRNA gene on chromosome X (6). Present at this site are insertions from each of the four S. cerevisiae retrotransposon families typically associated with tRNA genes or other genes transcribed by RNA Pol III. Arrows indicate the orientation of insertions or the direction of tRNA gene transcription.