COMMENTARY

Pushing the limits for the highest critical currents in superconductors

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The word "superconductor" (SC) evokes the best-known and most-impressive characteristic of these materials, namely their capability to transport electrical current without dissipation. Zero resistance, though, is not the most fundamental property of an SC and by no means has a trivial explanation. The defining phenomenon in an SC is the Meissner effect, which dictates that, in the presence of a low external magnetic field (H), the field inside the SC is zero (1). The Meissner effect implies that if H is high enough the SC phase will be destroyed, i.e., there is a critical field. At intermediate fields, a broad variety of SCs, called "type II," let most of the field penetrate in the form of "vortices," while most of the material remains superconducting. This trick allows the critical field to reach dramatically higher values, making these materials technologically useful (1, 2). But there is one problem: In a homogeneous SC, electric currents move the vortices, producing dissipation (resistance $R \neq 0$). This technologically detrimental motion can be precluded by the presence of material disorder, which produces "pinning centers" that trap the vortices, as long as the current density does not exceed a critical value, J_c (1–3). For five decades, the art and science of improving vortex pinning in SCs has progressed through educated guesses, theoretical modeling, and resource-intensive experimental optimization. Recently, enabled by more powerful computational capabilities and inspired by the "materials by design" new paradigm, an effort to advance toward a systematic "critical-currents-by-design" approach has been underway (4). In PNAS, Sadovskyy et al. (5) continue moving on that path but incorporate a radically different strategy. Starting from a "seed" pinning landscape, they apply a genetic algorithm to allow it to evolve toward a configuration with optimum J_c. By informing the engineering of the pinning landscape, this design tool may significantly reduce the experimental trial-and-error burden.

Superconducting vortices are fascinating nanoscale objects, each one carrying one magnetic flux quantum. They are tubes of currents whirling around a central core, analogous to tornadoes and vortices in liquids. In the SC, the "fluid" is the Cooper pairs of electrons that perform the nondissipative transport and which, being electrically charged, generate the vortex axial magnetic field. At the central core, the superconductivity is destroyed, and it is only in these tiny filaments where dissipation occurs when vortices move. Vortices repel each other. In a homogeneous SC, this results in a textbook-simple equilibrium configuration: the triangular Abrikosov lattice of straight parallel vortices, with a lattice parameter that decreases as H increases (1). But vortices are elastic; they can bend and entangle. They do that to allow portions of their cores to go through nonsuperconducting regions of the material (defects) so that their energy decreases (1–3). The interaction between one vortex and one defect is already a complex problem involving several parameters. But the real difficulty is that the lowest energy (strongest pinned) configurations are the result of the tradeoff of many vortices interacting simultaneously with many defects and with each other (3). The general optimization problem of determining the pinning landscape that produces the highest J_c for arbitrary temperature (T) and $\mathbf{H}$ is unsolved, and the answer to the related question of what is the highest J_c that can be achieved for given T-$\mathbf{H}$ is unknown. The study by Sadovskyy et al. (5) proposes a different approach: Let evolution find out. There are at least three attractive concepts involved in the method. First, it does not assume any a priori pinning model. Second, it may produce arbitrary combinations of defects. Third, it can be run starting from different seed pinning landscapes.

Several successful pinning models have been developed. They typically describe the effects of one type of disorder and can be broadly divided into strong and weak pinning. Conceptually, perhaps the simplest case is an array of parallel columnar defects (CDs), as discussed by Nelson and Vinokur (6). This is the best-known example of strong pinning. The CDs are very efficient when $\mathbf{H}$ is parallel to them, simply because they can pin long portions of the cores. At

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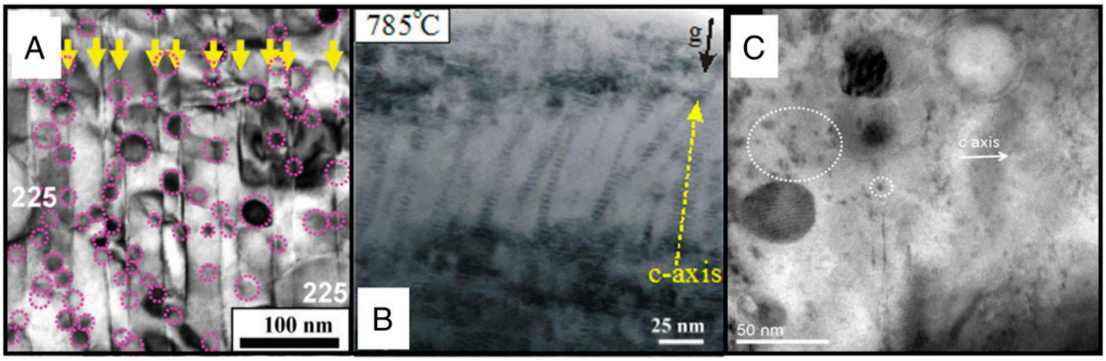

Fig. 1. Transmission electron microscopy images showing examples of complex pinning landscapes in $ReBa_2Cu_3O_7$-coated conductors grown by different methods. (*A*) Metal organic deposition (MOD) with artificially added $BaZrO_3$ nanoparticles. Reprinted with permission from ref. 12. Copyright 2011 by the American Physical Society. (*B*) Pulsed laser deposition with artificially added self-assembled $BaZrO_3$ nanorods. Reprinted with permission from ref. 14. (*C*) MOD with artificially added Dy_2O_3 NPs and irradiated with oxygen ions. Reprinted from ref. 22, with the permission from AIP Publishing. For detailed descriptions of the figures, see the respective references.

low vortex density (low H), a simple "one vortex, one defect" analysis is useful, but at high H and/or high T, the problem is collective, with bundles of vortices pinned by many CDs. The other limit is a very large density of randomly distributed small defects (e.g., point defects). In this situation, the pinning is always weak and collective, arising from statistical fluctuations of the defects' density. First developed by Larkin and Ovchinnikov (7) in the 1970s, these ideas were revised and expanded in the 1990s (3) as they were applied to describe pinning by point defects (such as oxygen vacancies) in oxide high-temperature SCs (HTSs). More recently, large attention has focused on randomly distributed larger defects, generically called nanoparticles (NPs) (8–10). Their popularity comes from the fact that they produce strong pinning that is rather isotropic (in contrast to CDs) and are easy to introduce artificially by chemical methods at industrial scale (11–13).

It is difficult to model combinations of different types of defects. The key problem is that pinning is not additive. It is well established that the strong pinning in thin films and coated conductors of the oxide HTS $YBa_2Cu_3O_7$ (which has the highest J_c of any known SC) is due to the presence of complex mixed pinning landscapes (12, 14) (Fig. 1), but a universal description is elusive. One advantage of the mixed landscapes is that different kinds of defects may have synergistic effects; for instance, the addition of NPs may preclude the propagation of low-energy depinning excitations characteristic of CDs (14). But there are also competing effects. In some T-$\mathbf{H}$ regimes, NPs may disrupt pinning by planar stacking faults (13), point defects may diminish the effectiveness of CDs (15) and NPs (16), and so on.

Some subtleties of the pinning landscapes are hard to anticipate. For instance, when we initially introduced CDs in $YBa_2Cu_3O_7$ single crystals by irradiation with 600-MeV Sn heavy ions, we observed a huge J_c enhancement (17). Transmission electron microscopy images showed that the amorphous tracks were slightly splayed (due to Rutherford scattering) and somewhat inhomogeneous in diameter along their lengths. Later, we used 1-GeV Au ions that produced more parallel and uniform CDs but were surprised to find out that the J_c increase was significantly lower. The solution to the puzzle came from a theoretical study by Hwa and coworkers (18) who realized that the splay had the beneficial effect of arresting the propagation of double-kink depinning excitations. Studies by Tamegai and colleagues in Tokyo (19) have shown that splay in the CDs can produce a rich and, in some cases, nonintuitive variety of pinning characteristics. One advantage of the evolutionary scheme is that no model is assumed, so none of these interactions needs to be explicitly introduced. The starting point may resemble a uniform random distribution of NPs, but the system is free to evolve into other landscapes, including mixed ones.

The capability of the scheme by Sadovskyy et al. (5) to start with an arbitrary seed landscape is also important because many defects appear spontaneously during fabrication (20). For instance, just in $YBa_2Cu_3O_7$, deposition methods that produce laminar growth (such as metal organic deposition) introduce planar stacking faults parallel to the *ab* planes (13), as well as rather large $RE_2Cu_2O_5$ precipitates (12). Methods that produce columnar growth, such as pulsed laser deposition, produce linear dislocations (20). Point defects and twin boundaries are present in all cases. Polycrystalline SCs such as MgB_2 wires contain grain boundaries (21). Thus, any attempt to enhance J_c by artificially incorporating defects in real SCs does not have the luxury to start from an empty space; preexisting defects with all their potential interplays (cooperative and competing) are unavoidable (11–16, 20, 22).

From a technological perspective, the most important question is, What is the highest achievable J_c under given T-$\mathbf{H}$ conditions? A simple calculation (3) suggests that, at low T and low H, a CD could produce J_c as high as the depairing current density J_d (at which the Cooper pairs break), but experimentally, the maximum attained J_c/J_d fraction is in the range of ∼0.3 (20, 23). It is quite telling that the best J_c/J_d fractions obtained by Sadovskyy et al. (5) are in the 0.3 to 0.4 range, even though there is nothing in the study pointing to the existence of a "hard barrier" at these values. Perhaps the conclusion is that this limit is just the result of vortices not being able to take full advantage of the available pinning due to the vortex–vortex repulsions. On the other hand, real pinning landscapes are more complex, and sometimes there is more than meets the eye. For instance, pinning associated with random NPs in $YBa_2Cu_3O_7$ is due in part to hard-to-visualize nanostrain in the matrix (24). Future developments of the evolutionary algorithm will certainly incorporate this type of subtlety. The problem is still open.

Acknowledgments

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