Nano Focus

Proton irradiation enhances critical features simultaneously in iron-based superconductors

Researchers at the Brookhaven National Laboratory in New York succeeded in simultaneously enhancing two counteracting properties of superconductors which are important for applications, the critical temperature and the critical current density. The phenomenon was observed in iron-based superconductors (IBSCs) irradiated with low-energy protons. The study, led by Qiang Li at Brookhaven, was published in *Nature Communications* (doi:10.1038/ncomms13036).

According to Toshinori Ozaki, now at Kwansei Gakuin University in Japan, the results open new possibilities for the production of low energy accelerators, which will be less expensive to purchase and maintain than currently available, as well as for new transmission and distribution cables that can be used for the upgrade of power grids.

In Type I materials, superconductivity is suppressed not only when temperature rises above the critical temperature (T_c), but also when the magnetic field rises above a critical value. Type II superconductors on the other hand, like the iron-based ones used by Li's team, can tolerate even strong fields, by allowing quanta of magnetic flux to penetrate them in the form of vortices. The penetration takes place near defects, around which non-superconductive areas are created.

The density of these non-superconductive regions, which reflects the ability of the defects to pin the vortices, is expressed through the critical current density J_c. Enhancing T_c is a challenging task, thus, much of the research for the improvement of superconductors has instead focused on raising J_c. But the more tolerant a material becomes to higher magnetic fields, the more its T_c is reduced. Increasing T_c and J_c at the same time, although highly desirable, is very difficult to realize.

Li's group has previously achieved very high J_c (>10^5 A/cm^2 under 30 tesla magnetic fields) in epitaxial thin films of $FeSe_{0.5}Te_{0.5}$ (FST), a type of IBSC. However, Li's group soon found that further controlling the defects and increasing J_c was increasingly difficult. The team decided to choose ion irradiation for the introduction of defects in the films. "The low energy proton irradiation which we used to bombard the superconductor material, as well as the aluminum foil, turned out to be the keys in this study," Ozaki says.

The researchers used pulsed laser deposition to grow FST films of 100–130 nm thickness with a CeO_2 buffer layer on $SrTiO_3$ single-crystalline substrates, and covered the films with a 1.5-mm-thick aluminum foil. The samples were subsequently irradiated with 190-keV protons at a dose of 1×10^{15} p cm^{-2}.

The low energy irradiation created cascade defects on the films and produced a strain field. This resulted in strong vortex pinning, which eventually raised J_c at both zero and high magnetic fields at all temperatures. For example, at 4.2 K, J_c doubled to about 2.5×10^5 A/cm^2 under a strong magnetic field of 35 T. Surprisingly the T_c was also enhanced by about 1 K.

"While the J_c enhancement is impressive but not completely unexpected, the T_c enhancement is extraordinary considering the common wisdom of T_c degradation by irradiation," says Paul Chu of the University of Houston and one of the first scientists to demonstrate high-temperature superconductivity in 1987. According to Chu, the attribution of the enhancement of T_c to the strain associated with the defects created by irradiation is consistent with the earlier positive pressure effect observed on the T_c of $FeSe_{0.5}Te_{0.5}$ thin films.

Hideo Hosono of Tokyo Institute of Technology, and the materials scientist who discovered IBSCs in 2006, says the idea that the stress generated by implantation enhances T_c looks reasonable if one keeps in mind the high sensitivity of T_c which Type II superconductors exhibit when they are epitaxially grown on the substrate. "The J_c of the implanted thin films exceeds [those of] the practical intermetallic superconductors at high magnetic fields, providing a new possibility of IBSCs for high field applications," he says.

For Pau Chu, Li's team achievement "is turning a seemingly inconspicuous simple superconductor into one with profound technological significance, thus suggesting that other superconductors might be similarly modified."

Ozaki says that for the team this piece of research has just been the beginning. "We are now going to experiment with the energy and the ion species, as well as with different kinds of superconducting materials, like high-temperature superconductors. We believe that by fine-tuning the defects morphology and the strain configuration, T_c and J_c can be further improved."

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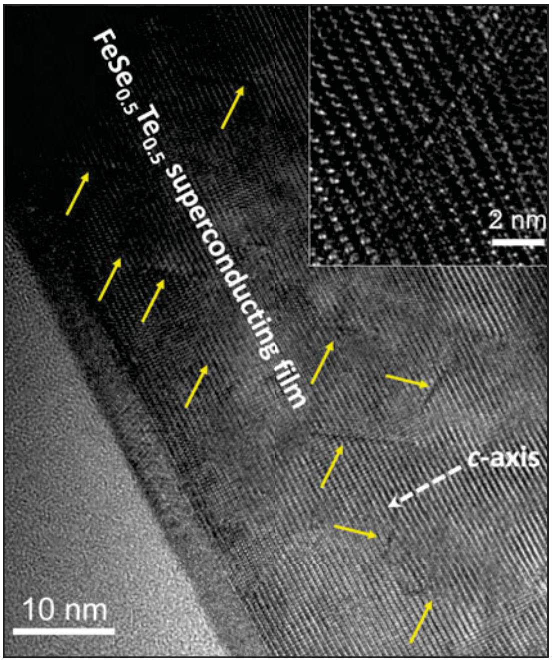

An electron microscope image of $FeSe_{0.5}Te_{0.5}$ iron-based superconducting films irradiated with low-energy protons. Yellow arrows designate the resulting chains of defects. The inset image shows a zoomed-in view of a typical defect chain. Credit: Toshinori Ozaki and Qiang Li.