

## 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<sup>2</sup> under 30 tesla magnetic fields) in epitaxial thin films

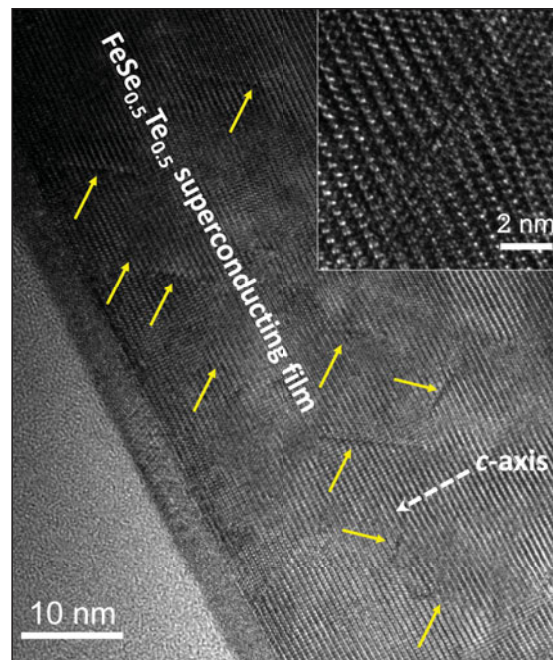
of FeSe<sub>0.5</sub>Te<sub>0.5</sub> (FST), a type of IBSC. However, Li's group soon found that further controlling the defects and increasing  $J_c$  was increasingly difficult. The team decided to choose ion irradiation for the introduction of defects in the films. "The low energy proton irradiation 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<sub>2</sub> buffer layer on SrTiO<sub>3</sub> 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  $1 \times 10^{15}$  p cm<sup>-2</sup>.

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  $2.5 \times 10^5$  A/cm<sup>2</sup> 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 Pau 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<sub>0.5</sub>Te<sub>0.5</sub> thin films.

Hideo Hosono of Tokyo Institute of Technology, and the materials scientist who discovered IBSCs in 2006, says



An electron microscope image of FeSe<sub>0.5</sub>Te<sub>0.5</sub> 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.

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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