The journey of high-temperature superconductors: From discovery to today

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John H. Miller, Jr., Professor of Physics at the University of Houston, discusses progress in high-temperature superconductors and its applications

The lab of H. Kamerlingh Onnes, the first group to liquefy helium, discovered superconductivity in 1911. Several metals were found to undergo a phase transition to a new state characterized by the loss of resistance below a critical temperature, or Tc. The Meissner effect, the expulsion of magnetic flux, was discovered in 1933. In 1957, John Bardeen, Leon Cooper, and J. Robert Schrieffer published a microscopic theory, now known as the BCS theory, [(1)] based on pairing of electrons mediated by phonons.

That same year, Abrikosov developed an improved understanding of the magnetic properties of superconductors, distinguishing between type-I (soft) and type-II (hard) superconductors. Most notably, he proposed the formation of flux vortices in a type-II superconductor exposed to a magnetic field. This prevents a magnetic field from driving the entire type-II superconductor into the normal state, enabling it to have a much higher upper critical magnetic field – important for applications such as magnetic resonance imaging (MRI), particle accelerators, and tokamak fusion reactors.

The maximum critical temperatures of elemental superconductors, intermetallic compounds, and alloys improved slowly until 1972-73, when a plateau was reached at 23 K. A breakthrough occurred in 1986 when J. Georg Bednorz and K. Alex Müller discovered superconductivity with a Tc, (onset) of 35 K in the copper-oxide La2−xBaxCuO4. [(2)] After that initial discovery, several groups explored related cuprates by varying the stoichiometry.

An exciting discovery occurred in 1987 in a collaborative effort between groups at the University of Houston (UH) and the University of Alabama – Huntsville. [(3)] They observed superconductivity with a Tc, (onset) of 93 K in a mixed phase Y-Ba-Cu-O ceramic. The specific high-Tc superconducting (HTS) phase (‘black phase’) was identified as YBa2Cu3O7 (YBCO or Y-123). It was soon realized that Tc’s of around 90 K could be achieved in many ‘123’ compounds of the form RBa2Cu3O7 (REBCO or R-123), where R is a rare earth. The Tc was advanced several times, up to 134 K in the mercury-based cuprate HgBa2Ca2Cu3Ox, (Hg-1223). [(4)] Additional HTS families, including iron-based superconductors, hydrides, and nickelates, have been discovered, but the cuprates remain the most promising for applications.

Efforts have also included work to develop high-quality thin films, wires, tapes, and bulk materials suitable for applications. Another key parameter, besides the Tc, is the critical current density, or Jc. Cuprates have the undesirable (or desirable, depending on application) feature that the critical current density is reduced across a grain boundary with a large misorientation angle. As a result, the Jc's of cuprate ceramics are quite low.

During the last several decades, progress has been made in improving the quality of these materials. High-quality, epitaxial REBCO thin films, with Jc's up to 5×106 A/cm2, can be grown on single crystal substrates. A fundamental challenge, however, is the impossibility of producing flexible single crystal tapes of kilometer lengths. Critical current densities of HTS films deposited directly on flexible metal tapes are polycrystalline and thus have critical current densities much too low for applications.

A key breakthrough – ion beam-assisted deposition (IBAD) – was developed in 1995 by a group at Los Alamos National Laboratory. By simultaneously applying an ion beam when a film is being deposited onto a polycrystalline substrate via, e.g., magnetron sputtering, the film's grains become aligned with small misorientation angles – becoming a nearly single crystal film. IBAD can be used to deposit a thin, 10-nm thick, magnesium oxide buffer layer. HTS REBCO tapes often consist of a flexible Ni-alloy (e.g., Hastelloy) tape, a stack of buffer layers, including the thin MgO IBAD film, a much thicker REBCO film, a silver overlayer, and copper stabilizing layers on both sides.

Critical currents and maximum lengths of REBCO HTS tapes have improved dramatically through improved process control. This includes the introduction of 'pinning centers' to prevent dissipative motion of flux vortices, which can nucleate by quantum mechanisms.[(5)] Much of this work has been carried out at the Texas Center for Superconductivity at the University of Houston (TcSUH) and UH's Advanced Manufacturing Institute (AMI), headed by Venkat Selvamanickam. REBCO tapes of kilometer length scales, with high critical currents and capable of sustaining high magnetic fields, can now be manufactured. They have been used to make power transmission cables, including some in live power grid demonstrations. A potential advantage is the ability to retrofit existing conduits with smaller, higher current capacity cables in a dense urban environment.

One of the most recent and exciting applications of REBCO HTS tapes draws on their extremely high upper critical magnetic fields. By using high field magnets wound with HTS tapes, one can potentially build a much more compact tokamak fusion reactor than would be possible with conventional superconducting magnets. Commonwealth Fusion Systems, in the Boston area, has successfully demonstrated a 20-T HTS magnet. It aims to achieve fusion energy break- even with its SPARC fusion reactor now under construction. Subsequently, the company plans to build a commercially viable ARC fusion reactor. Tokamak Energy, in Oxfordshire, UK, is a company that aims to use high-field HTS magnets to build commercially viable spherical tokamak fusion reactors. It plans to develop 500-MW fusion reactors that could be deployed starting in the 2030s.

References

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