High-Performance YBCO-Coated Superconductor Wires

M. Parans Paranthaman and Teruo Izumi,
Guest Editors

Abstract

This issue of *MRS Bulletin* provides an overview of the current status of research and development in the area of high-temperature superconductor (HTS) wires. High-temperature oxide superconductors, discovered in the late 1980s, are moving into the second generation of their development. The first generation relied on bismuth strontium calcium copper oxide, and the second generation is based on yttrium barium copper oxide, which has the potential to be less expensive and to perform better. The potential uses of HTS wires for electric power applications include underground transmission cables, oil-free transformers, superconducting magnetic-energy storage units, fault-current limiters, high-efficiency motors, and compact generators. Wires of 10–100 m in length can now be made, but material and processing issues must be solved before an optimized production scheme can be achieved. This issue covers a range of processing techniques using energetic beams, rolling, and laser and chemical methods to form wires with good superconducting properties.

Keywords: *coated conductors, high-temperature superconductors, YBCO,* $YBa_2Cu_3O_{7-\delta}$.

Since the discovery of high-temperature superconductors (HTSs) in the late 1980s, notably $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ (known as BSCCO or 2223) and $YBa_2Cu_3O_{7-\delta}$ (known as YBCO or Y-123), researchers all around the world have searched for ways to produce affordable flexible conducting wires with high current density. The U.S. Department of Energy's target price for these conductors is close to the current cost of copper wire at \$10/kA m USD.

The strategic goal is to achieve HTS wire with a current capacity 100 times that of copper. Robust, high-performance HTS wire would certainly revolutionize the electric power grid and various other electric power applications as well. One company, American Superconductor Corp. (AMSC), has been widely recognized as a world leader in manufacturing first-generation (1G) HTS wires based on BSCCO materials using the oxide-powder-in-tube (OPIT) process. AMSC has achieved electrical critical current (I_c), defined as the maximum current a superconductor can transport, of more than 125 A/cm-width in piece lengths of several hundred meters, and a "champion" current (the highest current achieved to date for this superconductor) of 170 A at 77 K and self-field in a wire at the standard 4.1 mm width and 210 μm thickness.[1] However, due to the higher cost—approximately \$300/kA m—of 1G wire, researchers worldwide shifted their efforts toward the development of second-generation (2G) YBCO wires.

One of the main obstacles to the manufacture of commercial lengths of YBCO wire has been the phenomenon of weak links: grain boundaries formed by the misalignment of neighboring YBCO grains are known to form obstacles to current flow. By carefully aligning the grains, low-angle boundaries between superconducting YBCO grains allow more current to flow. In fact, below a critical misalignment angle of 4°, the critical current density approaches that of YBCO films grown on single crystals.[2]

The schematics of 1G and 2G HTS wire architectures are shown in Figure 1. Several methods have been developed to obtain biaxially textured substrates suitable for high-performance YBCO films. They are ion-beam-assisted deposition (IBAD), the rolling-assisted biaxially textured substrate (RABiTS) process, and inclined substrate deposition (ISD). The industry standard for characterizing 2G wire is to divide the current by the width of the wire. With either a 3-μm-thick YBCO layer carrying a critical current density J_c of 1 MA/cm^2, or a 1-μm-thick YBCO layer carrying a J_c of 3 MA/cm^2, the electrical performance translates to 300 A/cm-width. (Critical current density is the maximum current density a superconductor can carry; beyond this value, it becomes non-superconducting.) Converting these numbers to the industry standard of 0.4-cm-wide HTS wire would correspond to 120 A in a 0.4-cm-wide tape, or 300A/cm-width. This performance level is comparable to that of the commercial 1G wire manufactured by AMSC. Further increases in thickness or critical current density, or finding a way to incorporate two layers of YBCO (either a double-sided coating or joining two YBCO tapes face to face) in a single-wire architecture would result in a performance exceeding 1G wires: a high overall engineering critical current density, J_E, at 77 K. "Engineering" critical current density includes the effects of non-superconducting substrates and buffers, whereas J_c is the critical current density of the superconductor layer only. The other important advantages of 2G YBCO wire over 1G wire include better in-field electrical performance at higher temperatures, potentially lower processing costs, and low ac losses.

The six articles in this issue provide an overview of the current status and future prospects for methods of producing YBCO-coated superconducting composite wires. The first three articles discuss detailed methods of fabricating oriented templates for growing high-performance YBCO-coated wires. The last three articles review high-rate YBCO deposition processes.

The early history of ion-beam texturing and the importance of different IBAD templates are reviewed in the article by Arendt and Foltyn. A schematic illustration of the IBAD process is shown in Figure 2. The ion beam is used to grow textured buffer layers onto a flexible but untextured metal, typically a nickel alloy. After the initial development of an IBAD process using yttrium-stabilized zirconia (YSZ) by Iijima et al.,[3] researchers at Los Alamos National Laboratory (LANL) improved the process

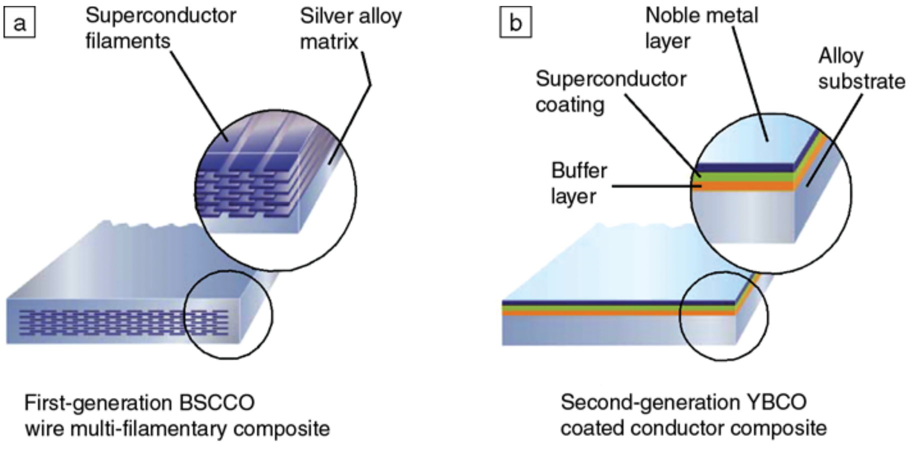

Figure 1. Schematic illustrations of (a) first-generation and (b) second-generation high-temperature superconducting (HTS) wire architectures.

and achieved high-performance YBCO films on IBAD-YSZ templates.[4] To date, IBAD templates of YSZ, gadolinium zirconium oxide ($Gd_2Zr_2O_7$, or GZO), and magnesium oxide (MgO) are being used to make YBCO tapes.

For IBAD-YSZ templating, a thick (~1.0 μm) YSZ buffer layer is needed to achieve the proper texture that will result in high J_c values in the subsequent YBCO films, but this requirement may limit the economical fabrication of long-length coated conductors. However, IBAD-MgO substrates exhibit good texture soon after nucleation, and only a ~10-nm-thick MgO film is needed to optimize the texture. But the texture development in an IBAD-MgO template depends strongly on the smoothness of the starting nickel alloy tapes. However, in collaboration with SuperPower Inc., LANL has already optimized reel-to-reel electropolishing of the Ni alloy substrates and has achieved substrates with a surface roughness of <1 nm. Perovskite buffers such as $LaMnO_3$, $SrTiO_3$, and $SrRuO_3$ have been found to be compatible with IBAD-MgO substrates. In a typical IBAD-MgO template, a total of five buffer layers are involved: an Al_2O_3 barrier; amorphous Y_2O_3 as the nucleation layer; an IBAD-MgO layer; and a homoepitaxial-MgO layer, involving the growth of MgO without ion-beam assist, followed by either $SrTiO_3$ or $LaMnO_3$. On IBAD-MgO templates, 1.4-μm-thick YBCO films with I_c values of 109 A (3.8 m length) and 144 A (1.6 m length) have been achieved.

The current status of the rolling-assisted biaxially textured substrates (RABiTS) process (see Figure 3) developed at Oak Ridge National Laboratory (ORNL) and the baseline architecture used are reviewed in the article by Goyal et al. The RABiTS process utilizes thermomechanical processing to obtain flexible, biaxially oriented nickel or nickel alloy substrates.[5] Buffers that transfer the texture of the metal substrate to the superconductor and prevent reaction between the substrate and the superconductor are deposited on the substrate. YBCO superconductors are then deposited epitaxially on the buffer layer. The starting substrate serves as a structural template for the YBCO layer, which has substantially fewer weak links than the substrate. For comparison, wires made by the OPIT process (1G wire) are expensive, since the major component is high-purity silver. In the RABiTS process, silver is replaced by low-cost nickel or a nickel alloy, which allows the fabrication of HTS wires at a lower cost.

The RABiTS architecture most commonly used consists of a starting template of biaxially textured Ni-W (3 at.% or 5 at.%) with a seed layer of 75 nm Y_2O_3, a barrier layer of 75 nm YSZ, and a cap layer of 75 nm CeO_2. In this architecture, all the buffers have been deposited by physical vapor deposition processes. However, efforts are being made to replace these layers with alternative architectures comprising multifunctional buffers deposited by industrially scalable methods. In addition, various thin-film deposition processes are explained in detail in Goyal et al.'s article. Recently, a high I_c of 250–270 A/cm-width with a standard deviation of 2.0–4.0% was achieved. For certain applications, it is necessary to start with completely nonmagnetic substrates such as Ni-9at.%W or Ni-Cr-W. Efforts are already under way to address these issues.

In a third template fabrication process, inclined substrate deposition, the textured buffer layers are produced by vacuum-depositing material at a particular angle on an untextured nickel alloy substrate. After the discovery of the ISD-YSZ process by Hasegawa et al. in 1996,[6] both Argonne National Laboratory (ANL)[7] and THEVA/Technical University of Munich, Germany,[8] improved reel-to-reel MgO buffer-layer texturing by ISD on Hastelloy tape. Ma et al.[7] have grown YBCO with a J_c of 1.2 MA/cm^2 at 77 K and self-field on short ISD-MgO templates with YSZ/CeO_2 buffers using pulsed laser deposition of YBCO. Recently, the THEVA group[8] has achieved 7–8° grain alignment in MgO-ISD tapes. By growing dysprosium barium copper oxide (DyBCO) films, they have achieved an improvement of 1–2° from the MgO layer using *in situ* electron-beam co-evaporation. A typical HTS coating thickness is 1.5–2.0 μm. They have also reported a critical current density of 2.3 MA/cm^2 in 20-cm-long tapes with an I_c level of more than 400 A/cm-width. Several-meter-long tapes exhibited J_c values of around 1.4–1.5 MA/cm^2 at 77 K and self-field.

Even though encouraging results have been obtained on ISD templates in short lengths, the basis for comparison in this review is the ability to produce long lengths of high-performance wire in a continuous process; thus, ISD is not discussed in-depth

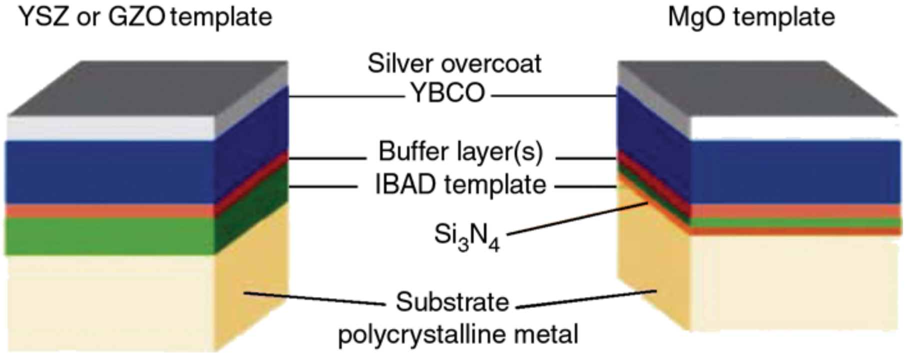

Figure 2. Schematic illustration of the ion-beam-assisted deposition (IBAD) process for fabricating YBCO superconducting wires using yttrium-stabilized zirconia (YSZ), $Gd_2Zr_2O_7$ (GZO), or MgO template architectures.

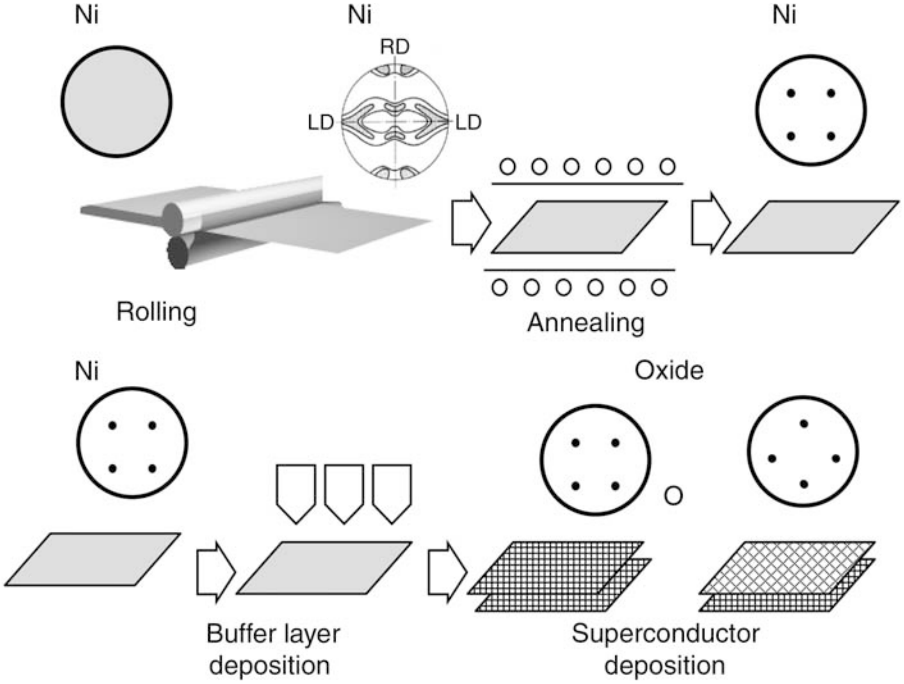

Figure 3. Schematic illustration of the rolling-assisted biaxially textured substrate (RABiTS) process. An untextured metal alloy is rolled and then annealed to produce a particular substrate texture. Epitaxial buffer layers (usually comprising a seed layer, a barrier layer, and a cap layer) are then deposited on the textured metal/alloy substrate. Epitaxial superconductors such as YBCO are then deposited onto the buffer layers. The circles labeled Ni show the pattern or orientation of the Ni grains at the various stages of the process; the wavy pattern of the Ni after rolling indicates the texture of the substrate after the first step; the dots inside the circle in later steps indicate a cubic orientation.

here. Both IBAD and RABiTS have the advantage over ISD in this regard. Recently, several organizations have demonstrated that they can produce 2G wires in 10–100 m lengths with I_c values ranging from 50 A/cm-width to 300 A/cm-width on either IBAD or RABiTS templates. Some of these results are outlined in this issue.

In the third article, Iijima et al. review the development history of the IBAD process from YSZ to GZO templates, and the related technologies for fabricating YBCO-coated conductors using IBAD, pulsed laser deposition (PLD), and trifluoroacetate-based metalorganic deposition (TFA-MOD). Pyrochlore-based GZO has a higher optimized deposition temperature of 200°C, as compared with the room-temperature deposition of YSZ (a temperature that is difficult to maintain during deposition because of the indirect heating from the source). Also, better in-plane textures were observed in GZO within a shorter time (as much as half the processing time of YSZ). Fujikura has produced 100 m lengths of YBCO tape by PLD on GZO templates with an average in-plane texture ($\Delta\phi$) of 10° at a tape speed of 0.5 m/h. In addition, self-epitaxial CeO_2 caps were produced on IBAD-GZO templates using PLD with a much improved texture ($\Delta\phi \sim 3°$) in a very short time. Self-epitaxy refers to textural improvement of the CeO_2 layer itself. Furthermore, no cracks were observed in CeO_2 layers. High-I_c YBCO films on CeO_2/IBAD-GZO templates were grown using both PLD and TFA-MOD. Especially in the TFA-MOD process, a high I_c of 292 A/cm-width was realized by the multicoating method.

The fourth article, by Rupich et al., reviews the development of high-performance YBCO growth using TFA-MOD. The MOD process involves four steps: precursor solution synthesis, coating, decomposition, and reaction. AMSC has achieved high-performance YBCO-coated conductors using MOD-YBCO and RABiTS templates. The most commonly used MOD process involves the use of yttrium, barium, and copper trifluoroacetates in methanol. The decomposition step involves a slow (10 h) burnout to reduce the volatility of copper trifluoroacetates. In addition, the YBCO film thickness is limited in this process to <0.5 μm. Hence, new copper precursors have been developed to reduce the volatility of the copper, reduce the fluorine content in the precursors, increase the thickness of the films, and shorten the YBCO processing time. Growth rates have been increased up to 4 nm/s for processing the YBCO films under reduced pressures. The MOD-YBCO films have a laminar microstructure, in contrast to the columnar microstructure of PLD-YBCO films. AMSC is routinely producing 10 m lengths (1 cm wide) of 2G wires using 0.8-μm-thick MOD-YBCO on RABiTS templates. However, it is a big challenge to produce ~1.5-μm-thick YBCO films in a single coat. The incorporation of dispersed nanodots (nanoparticles) of yttrium oxide in the YBCO matrix has been shown to enhance critical-current retention in magnetic fields. Enhancement of flux pinning in YBCO/REBCO (RE = rare-earth element) films has been of great interest in the HTS community in recent years.

In the fifth article, Selvamanickam et al. discuss the development of high-performance YBCO growth using metalorganic chemical vapor deposition (MOCVD). The MOCVD process has been widely recognized as a high-throughput method. However, the cost of starting precursors is still an important issue. SuperPower has achieved 18 m lengths of YBCO tapes with an end-to-end I_c exceeding 100 A on IBAD templates. They have also achieved high YBCO deposition rates of 12 nm/s with I_c values of 230 A/cm-width in short lengths. Rare-earth doping in HTSs has been evaluated as a method to improve flux pinning in these conductors. YBCO films with 10% samarium doping exhibit an I_c of 230 A/cm as compared with undoped YBCO films with an I_c of 193 A/cm. The observed *c*-axis peak, which represents the increased J_c at the zero angle at 77 K and 1 T (applied magnetic field), is also higher and broader for the doped sample than for the undoped sample. SuperPower is pursuing this MOCVD process for the commercial manufacture of coated conductors. Recently, SuperPower has also achieved 105 A/cm-width performance in a 57 m HTS YBCO wire, a result that is 60% higher than the previous high announced by Fujikura last year. In this case, the YBCO was deposited using PLD.

The last article, by Usoskin et al., discusses the development of high-performance YBCO growth using high-rate PLD (HR-PLD) on IBAD-YSZ templates. YBCO films with an I_c of 480 A/cm in short lengths and 360 A/cm in 6-m-long tapes have been achieved by using HR-PLD. Recently, it has been shown that tapes can be produced via HR-PLD at an increased film-deposition speed of 60 nm m^2/h (60 nm of YBCO film deposition in a square-meter area of tape in one hour). A deposition speed of 140 nm m^2/h is

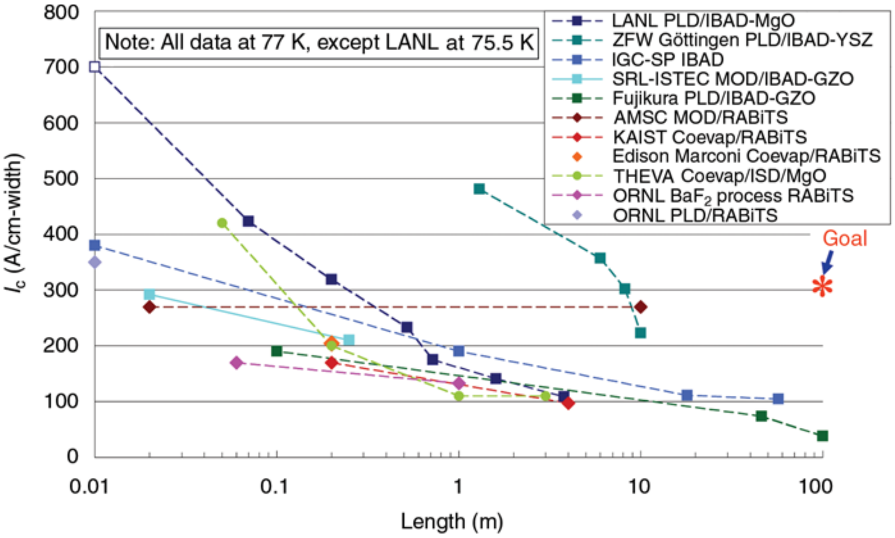

Figure 4. Electrical performance of second-generation high-temperature superconductor (HTS) wires. AMSC = American Superconductor (USA); Fujikura = Fujikura Ltd. (Japan); GZO = $Gd_2Zr_2O_7$; IBAD = ion-beam-assisted deposition; IGC-SP = IGC-SuperPower Inc. (USA); ISD = inclined substrate deposition; KAIST = Korea Advanced Institute of Science and Technology (Daejeon, Korea); LANL = Los Alamos National Laboratory (USA); MOD = metalorganic deposition; ORNL = Oak Ridge National Laboratory (USA); PLD = pulsed laser deposition; RABiTS = rolling-assisted biaxially textured substrate; SRL-ISTEC = Superconductivity Research Laboratory, International Superconductivity Technology Center (Japan); THEVA = THEVA Dünnschichttechnik (Germany); YSZ = yttrium-stabilized zirconia; ZFW = Zentrum für Funktionswerkstoffe Göttingen (Germany).

also possible. It is still a significant challenge to use the PLD process to fabricate lower-cost YBCO-coated conductors.

The electrical performance for currently available 2G HTS wires is shown in Figure 4.[9] This figure compares the performance of YBCO wires from various groups in the United States, Japan, Germany, and Korea. Some of the data in this plot are discussed in detail in this issue. Table I outlines the key issues related to the development of 2G YBCO superconducting wires, according to the Coated Conductor Development Roadmapping Workshop II, conducted last year by the U.S. Department of Energy.[10]

In summary, four different templates—IBAD-YSZ, IBAD-GZO, IBAD-MgO and RABiTS—have been developed for fabricating second-generation high-temperature superconducting wires. Manufacturers around the world are in the process of taking the technology to the pilot scale to produce commercially viable 100 m lengths. In addition, three different deposition methods—metalorganic deposition, metalorganic chemical vapor deposition, and high-rate pulsed laser deposition—have been used to demonstrate high I_c values in YBCO-coated conductor tapes of 10 m or more in length. The articles in this issue are aimed at providing the reader with a snapshot of these developments and a sense of their significance for electric power applications.

Table I: Recommended Design Parameters for Second-Generation YBCO Superconducting Wires for Use in Power Applications by 2010.

Geometry Specifications

- Face-to-face architecture
- Neutral axis
- Alternate conductor designs
- Conducting substrate
- Two-sided coating
- Current-carrying capacity of stabilizer
- Multilayers for low ac loss Multifilamentary; filament size, >10 μm
- Substrate thickness, 25–50 μm
- Piece length, 1000 m
- Width, <1 cm

Performance and Operation Specifications

- Engineering critical current density (J_E), 10,000–20,000 A/cm^2 at 30–65 K and 3 T
- Critical current (I_c), 1000 A/cm-width width at 77 K and self-field
- I_c at operation conditions, 100–200 A
- Stabilizer design, 200 MPa stress (300 MPa) at 77 K
- Irreversible strain limit, 0.6% tension, 1% compression (for magnets)
- 2 cm bend diameter
- n value $\geq 14^a$

Source: Reference 10.

^{a}n value is the exponent $V \sim I^n$ of the current–voltage characteristic ($I-V$ curve) at the transition from the normal to the superconducting state, measured at the industry standard value of 1 μV/cm.

Acknowledgments

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Paranthaman is one of the co-inventors of the rolling-assisted biaxally textured substrate (RABiTS) process for fabricating high-performance superconducting wires, which earned an R&D 100 Award in 1999. His present research focus is on the development of coated conductors using vacuum and nonvacuum processing techniques, materials synthesis, and characterization of high-temperature superconductors. He has authored or co-authored more than 230 publications in his area and has over 1500 citations to his work. He has given several invited presentations at national and international conferences. He holds 17 U.S. patents related to the RABiTS technology.

Paranthaman received his PhD degree in materials science and solid-state chemistry from the Indian Institute of Technology Madras in 1988. He was a postdoctoral fellow at the University of Texas Center for Materials Science and Engineering and a research associate in the superconductivity laboratories at the University of Colorado. He joined Oak Ridge National Laboratory in 1993.

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In 2001, Paranthaman was a member of the group that earned a Federal Laboratory Consortium Award and an Energy 100 Award from DOE. He was with the group that earned the 1997 Lockheed Martin NOVA Award for technical achievement. In 1997, Paranthaman was named Lockheed Martin Scientist of the Year. He has earned numerous other awards during his career at ORNL, which began in 1993. Earlier this year, he was named to the North American editorial board of *Superconductor Science and Technology*. He is also an associate editor for the *Journal of the American Ceramic Society*.

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He has published more than 150 papers related to superconductivity and silicon crystal research. He received the Best Paper of the Year Award from the Japan Institute of Metals in 1993. He is currently a member of the Materials Research Society, the Japan Institute of Metals, the Japan Society of Applied Physics, and the Cryogenic Society of Japan, and has been a principal editor of the *Journal of Materials Research* since 1995.

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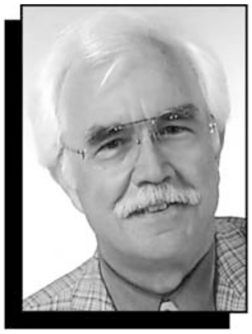

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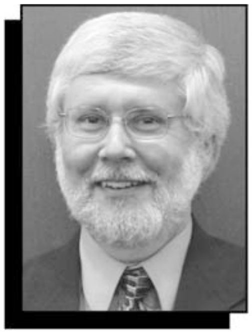

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Since the early 1990s, he has been developing second-generation HTSs based on buffer layers textured by ion-beam-assisted deposition and pulsed-laser-deposited YBCO. In 1990, he co-founded Zentrum für Funktionswerkstoffe (ZFW). Freyhardt studied physics at the University of Göttingen and served as a visiting scientist at Argonne National Laboratory. He has published a book series and more than 250 scientific papers, edited several proceedings, contributed to handbooks and textbooks, and holds 15 patents.

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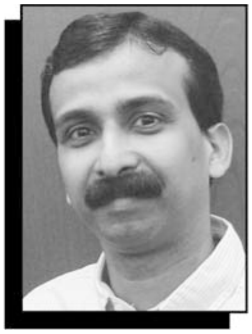
Goyal received a BTech degree in metallurgical engineering from the Indian Institute of Technology in 1986, an MS degree in mechanical and aerospace engineering from the University of Rochester in 1988, and a PhD in materials science and engineering from the University of Rochester in 1991.

Goyal is the lead inventor of the RABiTS process for fabricating high-performance superconducting wires. He holds 39 U.S. patents with 15 more pending, and four international patents with more pending, related to the RABiTS process. He was named a Battelle Distinguished Inventor in 2003. He has received numerous other awards, including a 2003 Exceptional Accomplishment Award from the U.S. Department of Energy, a 2001 Federal Laboratory Consortium Award, a 2001 Energy 100 Award, the 1999 MIT Technical Review TR100 Award, the 1999 ORNL Inventor of the Year Award, a 1999 R&D 100 Award, the 1997 Lockheed-Martin NOVA Award for technical achievement, and the 1996 DOE Materials Science Award for technical achievement in solid-state physics.

Goyal has authored or co-authored over 250 publications and conference proceedings. He has given five plenary talks, more than 90 invited presentations in national and international conferences, and has published over 30 invited papers and book chapters. He has co-edited four books on high-temperature superconductivity. His work

Yasuhiro Iijima

Kazuomi Kakimoto



Thomas Kodenkandath

Xiaoping Li

Jodi Reeves

Alexander Usoskin

Darren T. Verebelyi

Yiyuan Xie

Yutaka Yamada

Wei Zhang

has received more than 1000 citations from first- and second-author publications alone. He was a member of the advisory board for the Materials Research Science & Engineering Center of Excellence at Carnegie Mellon University during 1999 and 2000. He was a member by invitation on the panel of judges for the 2000, 2001, and 2002 R&D 100 awards. He was a member by invitation on the panel of judges for the 2000 DOE university project peer review as well as a member by invitation on the review panel for DOE, DARPA, and NSF programs. He has been a reviewer for numerous national and international technical journals. He has also organized many symposia and workshops and chaired numerous sessions in national and international conferences.

He was invited to teach/conduct a short course on superconductivity at the University of Talca in Chile in December 2000. He is a principal editor of the *Journal of Materials Research* and serves on the international advisory board of editors of the *Journal of the Korean Institute of Applied Superconductivity and Cryogenics*. He is also an associate editor for the *Journal of the American Ceramic Society*.

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