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Second generation YBCO coated conductors: A review

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Abstract **The advance in first generation Bi-2223 HTS wire has enabled the demonstration of superconducting power cables, magnetic energy-storage devices, transformers, fault current limiters and motors. However, the low irreversibility field (*H**) prevents application of Bi-2223 at 77 K in any significant field. Worldwide activities are therefore, focused on developing a second-generation HTS technology based on YBCO, for which *H** (77 K) ~ 7 T. In this paper, we discuss the status and commercial prospects of second generation HTS wire technologies. In addition, we review the recent results and discuss the prospects of future applications.**

Keywords: HTS, YBCO, Coated conductor, Bi-2223, application.

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In September 1986, A. Müller and G. Bednorz, two scientists at an IBM research center in Zurich, Switzerland, published a paper describing a copper-oxide compound that exhibited superconductivity at 35 K, 12 degrees above the Curie temperature of any superconducting material known to that time. In early 1987, superconductivity in $YBa_2Cu_3O_x$ (YBCO) at 92 K was announced. Soon T_c rose to more than 130 K in $Hg_2Ba_2Ca_2Cu_3O_x$. This moved the Curie temperatures of superconducting materials from the range of liquid helium temperatures (4.2 K) to those of liquid nitrogen temperatures (77 K). The reduction in cooling requirements promised to greatly reduce the cost of superconducting technology and widen its range of applications. Meanwhile, extensive efforts have been directed to the development of practical HTS conductors with high current carrying capability, first concentrating on the first generation (1G) $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) and now on the second generation (2G) YBCO based coated conductors[1—6]. The discovery by Akimitsu in 2001 that the binary compound MgB_2 with T_c =39 K has generated new interest in superconductors for power applications, owing to the abundance of Mg and B and the potential of analogous compounds[7].

Practical applications of superconductors have mainly focused on electric power systems and devices, such as power transmission lines, electric motors, and transformers. Thus, the optimization of these materials with respect to their superconducting properties seems to be in accord with the efforts to improve their stability in technical environments. Although there are obvious benefits from using high temperature superconducting (HTS) materials (most notably the potential for reduced energy losses in the conductors), a number of issues (such as overall system energy losses, cost, and reliability) may limit applications of HTS equipment, even if the well-known materials problems are solved.

1 Conductor requirements for power technology

Conductors for power applications are wires or tapes of high temperature superconductor and metal. Such wires must have sufficient strength to withstand the fabrication process, device winding, cool-down and electromagnetic stresses, and be capable of being made or cabled to sufficient size to carry operating currents from hundreds to thousands of amperes at costs comparable to Cu. In a word, HTS conductors must be reliable, robust and low cost with low AC-losses[1—6]. Using one standard measure based on the price of transmitting current over a meter, 1G Bi-2223 HTS wire is in commercial production now with a price of \$100—150/kA·m. Experts expect large-scale manufacture to drive the cost down to \$50/kA·m. 2G YBCO HTS wire would have the potential to meet a \$10/kA·m price/performance target. In addition, it is estimated that MgB_2 wire will eventually match NbTi's cost of \$1/kA·m, making it cheaper than copper wire (\$10—25/kA·m). These requirements define a parameter set that restricts present choice to Bi-2223, YBCO or MgB_2. The combination of critical current density Jc, field and operating temperature is summarized in Table 1[6]. Depending on applications, engineering critical current density, J_e (J_c averaged over the whole cross-section of HTS composite) must attain 10^4—10^5 A·cm^2 in fields of 0.1—10 T at temperatures of 20—77 K.

2 HTS wire and its development

Since 1986, over 100 HTS materials have been discovered, among which Bi-2223, YBCO or MgB_2 are regarded as most practical conductors for power applications. Commercial 1G HTS wire has a multifilamentary composite architecture. 2G HTS wire has a coated conductor composite architecture. Both architectures are composites of HTS materials with one or more metals or alloys.

Both Bi- and Y-based oxide superconductors have complicated crystal structures. They contain up to 4 or 5 chemical elements and are of layered perovskite structure, i.e. they consist of CuO_2 planes separated by other planes of insulating rare-earth elements or other oxides. Owing to the layered structure, HTS materials exhibit strong anisotropic electromagnetic properties, with $j_{c,ab} >> j_{c,c}$. HTS materials belong to type II superconductors. The most important property of type II materials is that they have higher critical fields than type I materials, which makes them suitable for many advanced applications. In addition,

Table 1 HTS wire performance requirements for various power applications

Application	J_c/A·cm^{-2}	Field/T	Temp./K	I_c/A	Wire length/m	Strain (%)	Bending radius/m	Cost/$·kA^{-1}·m^{-1}
Fault current limiter	10^4	0.1—3	20—77	10^3—10^4	1000	0.2	0.1	10—100
Motor	10^5	4—5	20—77	500	1000	0.2—0.3	0.05	10
Generator	10^5	4—5	20—50	>1000	1000	0.2	0.1	10
SMES	10^5	5—10	20—77	10^4	1000	0.2	1	10
Cable	10^4	<0.2	65—77	100 per strand	100	0.4	2	10—100
Transformer	10^4	0.1—0.5	65—77	10^2—10^3	1000	0.2	1	10

their properties at low temperatures are much higher than those of low temperature superconducting (LTS) materials.

Figure 1 shows HTS conductors that have been developed with the potential to become practical conductors. The J_c of 2G YBCO is very high, about 10^6 A/cm^2, and the material could remain superconductive in relatively high magnetic fields. Unfortunately, so far attempts to fabricate practical superconducting wires from YBCO have failed, since its irregular grains are difficult to work into tapes and wires due to weak link behavior. Worldwide efforts have, therefore, been to develop process routes to 2G HTS that is textured with extended overlapping of grains so that a global current could be efficiently transferred from one grain to the next. On the other hand, 1G Bi-2223 has flat, regular grains that can be more easily aligned, and proved much easier to fabricate, although it does not have nearly the current capacity of YBCO.

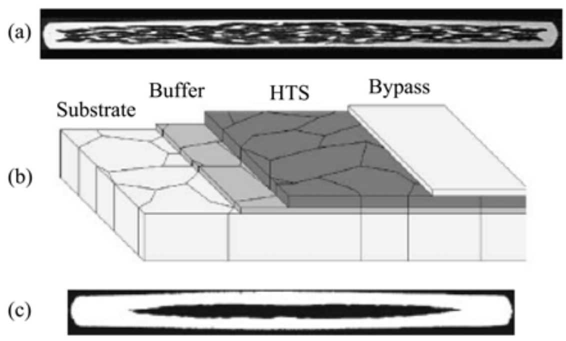

Fig. 1. HTS conductors developed for power applications. (a) BSCCO/Ag, (b) YBCO, (c) MgB_2/Fe.

(i) 1G HTS wire. At present, the only HTS conductor in production is Ag-sheathed Bi-2223 with T_c ~108 K. The tape-shaped wire is manufactured by a deformation process involving drawing and rolling, similar in many respects to the process used for wires or sheets of normal metals like copper and aluminum. So far thousands of meters of 1G multi-filamentary HTS wires have been fabricated by the oxide-powder-in-tube (PIT) process. Maximum I_c over lengths greater than 200 m even reaches 145 A and their J_e is about 15000 A/cm^2[4]. USA, Japan, Germany and China can produce long-length 1G HTS wire. AMSC is expanding its 1G wire manufacturing capacity with the commissioning of its new manufacturing facility in Devens, Massachusetts (20000 km/a)[4]. This driver is low cost. 1G HTS wire is expected to reach a price/performance of $50/kA·m (at 77 K, sf) in the Devens manufacturing plant at full capacity. Full-scale prototypes of electric power cables, motors, transformers, and other heavy electrical gear made with HTS wire have been built, primarily using the Bi-2223 conductors.

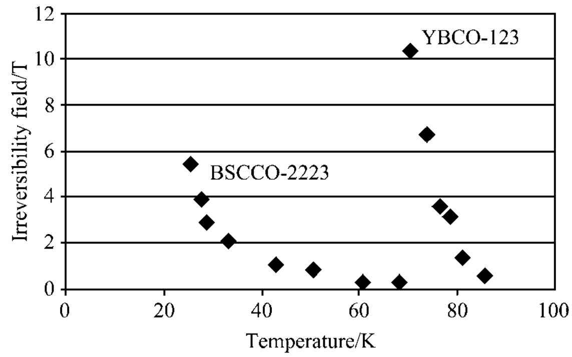

Fig. 2. Irreversibility fields for Bi-2223 and YBCO conductors.

Unfortunately, the strongly anisotropic Bi-2223, i.e. the temperature dependence of the irreversibility field (H*(77 K) ~ 0.2 T), appears to limit it to applications at lower temperature (< 40 K) or in low fields at higher temperature[6]. Compared to Bi-2223, YBCO will enable applications at 77 K and in magnetic fields over 1 T (H*(77 K) ~ 7 T) as shown in Fig. 2, fundamentally because of the different coupling between adjacent sets of Cu-O planes in the atomic structure of these materials. This is the main reason for developing a 2G HTS technology based on YBCO worldwide. In addition, the silver sheath substantially increases the cost of B-2223 wires, thus having an eventual $50/kA·m even the production is scaled up and yields are optimized. Other potential YBCO advantages are listed as follows: The alternating current (ac) losses in certain configurations could be lower, and the wire could be configured more easily to provide fault current limiting behavior.

(ii) 2G HTS wire. Second generation (2G), coated conductor composites under development today typically comprise a nickel-based alloy substrate and one or more micron-thick layers of the HTS materials. 2G wire can be formed by a variety of processes; however, in all cases, the manufacturing process comprises a series of steps to yield a crystallographically aligned coating of the HTS material. Recently, several novel approaches based on vapor deposition technologies very different from PIT, known as the ion-beamassisted deposition (IBAD) and rolling-assisted biaxially textured substrate (RABiTS) processes, have been developed and used to make YBCO films on metallic substrates by which high J_c values greater than 10^6 A/cm^2 were already demonstrated for short length samples. A key issue in the above approaches is the necessity to use buffer layers, whose function is mainly to prevent diffusion of metal elements into the superconductor during high-temperature processing and also transfers the biaxial texture of the metal substrate to the HTS coating.

In fact, the history of developing 2G wire to a great extent is a history of searching for these low-cost alternative processes, one for the substrate with the textured interface, and one for the superconductor layer itself.

(1) The substrate and textured buffer layers

i) IBAD. Fujikura in Japan developed it in 1991[8], and subsequently Los Alamos National Laboratory (LANL) optimized the IBAD-YSZ/PLD-YBCO process and achieved J_c up to 1 MA/cm^2 at 77 K in short samples[9]. IBAD is a method for obtaining biaxially textured films by simultaneously ion beam bombardment to the film surface during growth. This well-textured templates by IBAD can solve the “weak-link” problem of the YBCO and derive high performance in transport current property. The YBCO based on IBAD templates has aroused much attention because of its high critical current, length and reproducibility. However, the deposition rate of YSZ layer is extremely slow and not suitable for applications. LANL has been trying to use MgO instead of YSZ in order to quickly deposit the template. However this requires near-atomic smoothness of the substrate, a significant obstacle for a practical long-length wire manufacturing process. Recently, Fujikura is trying another alternate material, gadolinium zirconate or GZO which can be deposited in an IBAD process at twice rate of YSZ[10].

ii) RABiTS. Cube-texture of a Ni (or alloy) substrate tape is generated by conventional rolling with heavy deformation (> 95 %) to a roll textured tape, followed by an annealing step which results in a recrystallization into the desired biaxially textured cubic phase. With a CeO_2/YSZ/CeO_2 buffer system J_c (77 K, 0 T) > 1 MA/cm^2 has been achieved in small samples[11,12]. Unfortunately, the use of multi-buffer layer not only introduces significant complexity to the fabrication process, but also increases the cost. In addition, two challenges have been met by using very pure starting materials and a clean-room environment for the deformation processing, and in achieving an adequately smooth surface. Recently, much progress has been made in developing highly strengthened, less magnetic substrates.

iii) ISD. Inclined substrate deposition (ISD) achieves biaxial alignment of the YSZ buffer without assistance of an additional ion-beam using a high rate laser deposition and appropriate inclination of the metal substrate with respect to the laser plume[13]. This approach allowed a very high deposition rate, which reduced the substrate cost significantly. However, the degree of texturing, and correspondingly the electrical performance, has rarely matched that achieved by other methods: J_c (77 K, 0 T) ~ 1 MA/cm^2 has been achieved up to now only in short samples.

iv) Silver and silver alloy. Silver is the only substrate that does not need buffer layers[14]. Textured Ag substrates could be obtained by using a deformation process involving rolling and recrystallization annealing. Epitaxial YBCO was directly deposited on top of the textured silver substrate and achieved modest current carrying capacity.

(2) High J_c superconducting layers. There are many processes for making YBCO films. Typical ones are pulsed laser deposition (PLD), thermal evaporation, metal-organic vapor deposition (MOCVD), sputtering or ex situ electron beam processing, metalorganic deposition (MOD) and the sol-gel process. Among them, PLD is predominant for fabricating YBCO films and it has produced YBCO films with a relatively high performance of 400—500 A/cm-width in centimeter-length samples. However, PLD has two intrinsic problems: it requires an expensive vacuum system and the high-power UV laser is also expensive to run. Sputtering also faces the fundamental challenge of high vacuum-system cost. A lower vacuum and therefore potentially lower cost technique is metal-organic vapor deposition (MOCVD). While the deposition rate is rapid, uniformity over large areas and the precursor cost, involving complex organic molecules, remain unsolved problems.

From the viewpoint of high performance, low cost large scale manufacturing, the non-vacuum TFA-MOD process is getting more and more attractive[15]. TFA precursors with the Y, Ba and Cu cations are mixed in stoichiometric proportions in an alcohol solvent with the desired viscosity and applied either by spin-coating for short samples or slot-die web coating for long lengths (Fig. 3). The process is an *ex-situ* process, in the sense that subsequent furnace treatments are required to first decompose and then react with the precursor to form YBCO. MOD process is compatible with high rate low-cost ($10/kA-manufacturing). No material is wasted. No vacuum system is needed. Further, MOD process is scalable to long length, continuous processing[12].

Recently, IBAD/PLD (or MOCVD) techniques have made progress much highway. Continuous deposition of

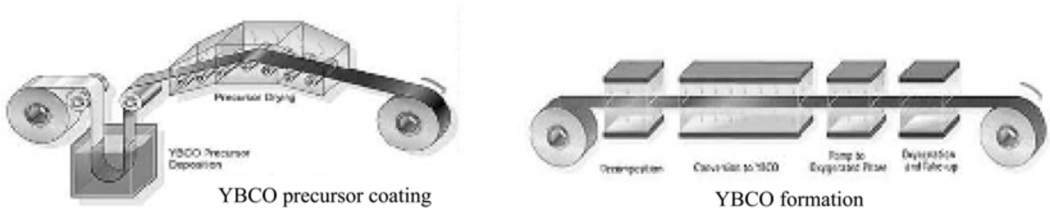

Fig. 3. Process of MOD for YBCO, no vacuum system is needed.

YBCO films were performed by PLD on long IBAD template tapes at a tape speed of 4.0 m/h. The 46 m YBCO coated tape with an I_c value of 74 A and J_c(77 K, 0 T) = 0.5 MA/cm^2 has been fabricated[10]. This is attributed to long length production with 100 m of IBAD GZO (t = 1.2 μm, rate = 0.5 m/h) template with $\Delta\phi$ = 10°. IGC-Superpower in USA has achieved J_c in 57 meter-length tapes as high as 10^5 A/cm^2 by IBAD-MgO/MOCVD. 10 m-length tape with I_c = I78 A (77 K, 0 T) and J_c=2.2 MA/cm^2 was fabricated by the University of Goettingen in Germany using IBAD/PLD[12].

As indicated above, the equipment and process cost of vacuum deposition, which is required for IBAD/PLD, are very high; therefore, USA, Japan and Europe are currently developing in a process to manufacture long wire using TFA-MOD process. In February 2004, AMSC achieved electric performance in multiple 10-m lengths of electrically and mechanically stabilized wire in the range of 250—270 A/cm width using MOD. By June 2004, AMSC had also produced short lengths of neutral axis 2G wire with an electrical performance of 330A/cm-width at liquid nitrogen temperature. The electrical uniformity and reproducibility of these MOD wires, fabricated in a reel-to-reel production process are excellent, laying the basis for both expanding production in its manufacturing development plant capable of producing hundreds of thousands of meters of 2G HTS wire per year[12]. Clearly, the low cost MOD processed YBCO wire is very promising for large-scale applications.

The United States, Japan and Europe are dedicating significant resources to development of HTS materials and applications through private industries, national laboratories and universities. Europe is making greater strides in YBCO development with the help of greater government funding, and Japan is performing the NEDO project with a budget of nearly $30 million in order to develop 2G HTS wires. The goal of this project is to realize the thousand-meter long 2G tapes around 2006. The U.S. Department of Energy started its Accelerated Coated Conductor Initiative (ACCI) works to quickly develop 2G coated conductor. According to ACCI, commercially viable, 2G HTS wire will be produced between 2006 and 2010, with final wire cost of $10 kA·m. Once affordable wire is available, HTS power cable is expected to be the first application to enter the market, followed by electric motors, generators and transformers.

(iii) MgB_2 wire. A promising new HTS, "magnesium diboride (MgB_2)", was discovered in 2001 by a team of Japanese materials researchers. Although it has a T_c of only 39 K, it is cheap, easy to fabricate, and much easier to work into wires than other HTS materials. The low T_c is a drawback, but it at least allows MgB_2 to be chilled with a mechanical cryocooler system rather than liquid helium. For MgB_2/Fe by PIT, critical current densities were achieved as high as 10^6 A/cm^2 at 4.2 K, 0 T and 10^4 A/cm^2 at 4.2 K and 6.5 T[16—17]. MgB_2 suffers from a low critical current density and poor resistance to magnetic fields, but researchers are making progress in both areas.

3 Applications and prospects

While HTS technology is still in the research and development phase, it offers many promising applications:

(i) Energy (cable, motor, generation, fault current limiter, etc.). Electric power systems offer the greatest potential in the near future, and indeed are the primary application for HTS. Because of its efficiency and high capacity, HTS technology has the potential to increase stability and reliability of the electric grid. Researchers are now demonstrating full-scale prototypes of electric power cables, motors, transformers, and other heavy electrical gear made with HTS wire. These prototype systems waste much less energy than existing technology; are generally smaller, lighter, and safer; and in some cases are more environmentally benign.

(ii) Transportation and national defense (superconducting MagLev, ship propulsion, MHD-based electrical power for hypersonic vehicles, fighter-class lasers, airborne kinetic energy, etc.). In transport applications, the main research effort is currently focused on vehicles able to levitate on magnetic field. HTS electromagnets would reduce power losses and would generate magnetic fields strong enough for levitation. In China, a first man-loading HTS Maglev test vehicle was tested successfully with up to five people and a total weight of 530 kg at a net levitation gap > 20 mm on a 15.5 m long guideway consisting of two parallel permanent magnetic tracks. HTS technology can also be applied to magnetohydrodynamic propulsion of, e.g., ships. The technology is based on generation of a thrust by passing current through a conducting fluid in the presence of a magnetic field.

(iii) Other applications (medicine, electronics, SQUID etc.). Superconducting magnets are nowadays used almost everywhere there is a need of high magnetic fields. Typical examples include magnetic resonance imaging (MRI), high-energy particle accelerators, chemical processing, and thermonuclear fusion research. In mobile phone communication systems, HTS microwave filter subsystems are already a commercially available solution for problematic radio reception situations.

A recent report forecasted[18] tremendous market penetration and corresponding annual savings due to HTS devices ($500 million by 2010 and > $10 billion by 2020). The study expected the highest market to be for HTS motors (market penetration 1% in 2006 rising to 79% in 2020). For other applications, the projections for the market penetration in 2020 are: transformers (76%), generators (50%), and underground power cables (80%).

However, cooling is the main concern for a future breakthrough of HTS applications. The market acceptance for HTS-based systems will depend critically on the availability of reliable and inexpensive cooling systems that are "invisibly" integrated in these systems.

4 Conclusions

1G Bi-2223 HTS wire is available commercially today in different product forms. However, the low irreversibility field prevents the use of Bi-2223 at 77 K in any significant field. The other problem with 1G is that it has to be encased in silver, which makes it 20—30 times more expensive than copper wire. Therefore, the limited potential for low cost production and still high AC-losses are the major obstacles to its wide application. 2G HTS based on YBCO represents the strongest candidate because of its potential of low cost. Intense work is being directed to development of low cost high volume processes, mainly through obtaining a well-textured microstructure and enhancing the current carrying capability across grain boundaries. MgB_2 seems a really low cost conductor, but only suited for a temperature range of 20—30 K. In a word, HTS is a new innovative technology that has great potential to make the electric system more efficient and reliable.

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