Superconductivity and its applications

Lecture 9

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Previously, in lecture 8 - HTS materials for applications

<table>
<thead>
<tr>
<th></th>
<th>Bi2212</th>
<th>Bi2223</th>
</tr>
</thead>
<tbody>
<tr>
<td>a [Å]</td>
<td>5.415</td>
<td>5.413</td>
</tr>
<tr>
<td>b [Å]</td>
<td>5.421</td>
<td>5.421</td>
</tr>
<tr>
<td>c [Å]</td>
<td>30.880</td>
<td>37.010</td>
</tr>
<tr>
<td># of adjacent CuO₂ planes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$T_c$ [K]</td>
<td>91</td>
<td>110</td>
</tr>
</tbody>
</table>
Previously, in lecture 8

HTS materials for applications

Copper oxides with highly anisotropic structures, **texturing** (grain orientation) is required in technical superconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ [K]</th>
<th>Texture</th>
<th>Produced by Powder-In-Tube method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi2223</td>
<td>110</td>
<td>c-axis</td>
<td>Ag matrix material</td>
</tr>
<tr>
<td>Bi2212</td>
<td>91</td>
<td>c-axis (radial)</td>
<td>Tape geometry to achieve c-axis texturing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$I_c$ depends on the magnetic field orientation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Round wire, spontaneous radial texturing of the c-axis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Isotropic properties of $I_c$</td>
</tr>
</tbody>
</table>
Previously, in lecture 8

**Bi2212 & Bi 2223 conductor technology**

**Bi2223 route**

Bi2223 conductors are multifilamentary tapes

**Bi2212 route**

Bi2212 conductors are multifilamentary round wires
Previously, in lecture 8 - HTS materials for applications

Bi2212
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$

Bi2223
$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}$

Y123
$\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

<table>
<thead>
<tr>
<th></th>
<th>Bi2212</th>
<th>Bi2223</th>
<th>Y123</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ [Å]</td>
<td>5.415</td>
<td>5.413</td>
<td>3.8227</td>
</tr>
<tr>
<td>$b$ [Å]</td>
<td>5.421</td>
<td>5.421</td>
<td>3.8872</td>
</tr>
<tr>
<td>$c$ [Å]</td>
<td>30.880</td>
<td>37.010</td>
<td>11.680</td>
</tr>
<tr>
<td># of adjacent CuO$_2$ planes</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>$T_c$ [K]</td>
<td>91</td>
<td>110</td>
<td>92</td>
</tr>
</tbody>
</table>

$b \approx 1.001 \; \text{in BSCCO}$

$b \approx 1.02 \; \text{in YBCO}$
Grain Boundaries in Y123
Grain boundaries in Y123

For angles above 8-10°, the $J_c^\text{GB}$ is reduced by a factor $>100$ !!

In order to get high $J_c$ in the conductor, the c-axis texturing is not enough

We do need also texturing in the ab plane

Hilgenkamp and Mannhart, RMP 74 (2002) 485
HTS conductors: texturing in Bi2223 and Y123

Both in Bi2223 and Y123, c-axis texturing is required due to the anisotropy of the properties //ab and //c

Because of the $J_c$ dependence on the GB angle in the ab plane, also in-plane texturing is required for Y123

This biaxial texture is required over kilometers!!
YBCO (REBCO) coated conductors

Cu stabilisation

Ag cap layer

REBCO layer

buffer layers

metallic substrate

~1 µm of REBCO in a ~100 µm thick tape

The template is a metallic substrate coated with a multifunctional oxide barrier

Biaxial texturing – within < 3° – is obtained

but with some also drawbacks:

• pronounced anisotropic behaviour
• complex and expensive manufacturing process

Presently produced by
The technology of REBCO coated conductors

Alternative approaches for growing epitaxial REBCO on flexible metallic substrates in km-lengths

Substrate texturing

- **RABiTS**: Rolling-Assisted, Biaxially Textured Substrates
  Texture is created in NiW by a rolling-and-recrystallization process

- **IBAD**: Ion Beam Assisted Deposition
  A biaxially textured MgO layer is grown on polycrystalline Hastelloy

Physical routes

- **PLD**: Pulsed Laser Deposition
- **RCE**: Reactive Co-Evaporation

REBCO layer deposition

Chemical routes

- **MOD**: Metal-Organic Deposition
- **MOCVD**: Metal-Organic Chemical Vapor Dep.
REBCO conductor technology: RABiTS template

RABiTS: Rolling-Assisted, Biaxially Textured Substrates

- [100] cube texture is created in the NiW substrate by a rolling-and-recrystallization process

- Several epitaxial buffer layers are needed to provide a lattice matched surface for growing the HTS layer
**REBCO conductor technology: IBAD template**

**IBAD : Ion Beam Assisted Deposition**

- A biaxially textured MgO layer is grown on a polycrystalline Hastelloy tape
- Several other buffer layers are needed to provide a lattice matched surface for growing the HTS layer
Performance overview: $J_c(s.f.,77K)$ vs. $J_c^{\perp}(19T,4.2K)$

$15$ mol. % Zr-added (Y,Gd)BCO

Xu et al., APL Mat. 2 (2014) 046111
Artificial pinning to enhance REBCO performance

Introduction of artificial nano-defects to control vortex pinning, reduce anisotropy and enhance performance

\( \text{BaZrO}_3 (\text{BZO}) \) precipitates are in form of nano-columns oriented along the c-axis

Driscoll et al., Nat. Mat. 3 (2004) 439
Goyal et al., SuST 18 (2005) 1533
Selvamanickam et al., IEEE TAS 21 (2011) 3049
On the BZO nanorods morphology

Selvamanickam et al., APL 106 (2015) 032601

Average BZO size 5.5 nm
Average spacing ~ 12 nm
Density = $6.9 \times 10^{11} \text{ cm}^{-2}$

No loss of BZO alignment in 2.2 μm thick films
**Engineering vs. superconducting layer performance**

*Engineering current density*

*Critical current density*

*REBCO and Bi2223 tapes retain the anisotropic properties of the superconductor*

*Data shown here correspond to the unfavorable orientation wrt the field*

*The in-field properties of Bi2212 wires are fully isotropic*
Industrial superconductors: $J_e$ Comparison

$J_e = \frac{I_c}{S_{tot}}$

August 2017

http://fs.magnet.fsu.edu/~lee/plot/plot.htm
## Industrial superconductors

### React&Wind vs Wind&React

<table>
<thead>
<tr>
<th>React&amp;Wind</th>
<th>Wind&amp;React</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NbTi</strong></td>
<td><strong>Nb$_3$Sn</strong></td>
</tr>
<tr>
<td><strong>ex situ MgB$_2$</strong></td>
<td><strong>in situ MgB$_2$</strong></td>
</tr>
<tr>
<td><strong>Bi2223</strong></td>
<td><strong>IMD MgB$_2$</strong></td>
</tr>
<tr>
<td><strong>Y123</strong></td>
<td><strong>Bi2212</strong></td>
</tr>
</tbody>
</table>
How to choose the superconductor: **Performance vs Cost**

![Graph showing the price/performance of different superconductors vs magnetic field strength.](graph)

\[
\frac{\$}{kA \cdot m} = \left( \frac{\rho}{J_{\text{eng}}} \right) \times \frac{\$}{kg}
\]

Adapted from B. Seeber, IEEE TASC 28 (2018) 6900305
Superconductor Technology
Basic design and operation issues of a superconducting device

Superconducting magnets, field shapes and winding configurations

- Solenoids (NMR, MRI and laboratory magnets)
- Transverse fields (particle accelerators)
- Toroids (fusion magnets)
Biot-Savart law \[ \mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \mathbf{l} d\mathbf{l} \times \mathbf{r} \]

In the case of a solenoid

\[ B_0 = J a F(\alpha, \beta) \]

where

\[ J = \frac{N I}{2 l (b - a)} \]

\[ F(\alpha, \beta) = \mu_0 \beta \ln \left[ \frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \right] \]

with \( \alpha = \frac{b}{a} \) and \( \beta = \frac{l}{a} \)

* Overall current density, normalized to the winding section including wire matrix and insulation
A given field can always be made by a short fat coil or a long thin one.

\[ B_0 = J a F(\alpha, \beta) \]

\[ \beta = \frac{l}{\alpha} \]

\[ V = 2\pi l(b^2 - a^2) \]

\[ = 2\pi a^3 (\alpha^2 - 1)\beta \]

\[ \alpha = \frac{b}{a} \]
Maximum field on the winding

$\alpha$ and $\beta$ have an influence on the field uniformity

At the exercise session: how to choose $\alpha$ and $\beta$ when designing a solenoid
Homogeneity of the field along \( z \)

\[ B_0 = J a F(\alpha, \beta) \]

where \( \alpha = \frac{b}{a} \) and \( \beta = \frac{l}{a} \)

How to calculate the variation of field along the axis of a solenoid

\[ B_z = \frac{1}{2} J a F(\alpha, \beta_1) + \frac{1}{2} J a F(\alpha, \beta_2) \]

\[ \beta_1 = \frac{l+z}{a} \]

\[ \beta_2 = \frac{l-z}{a} \]
Homogeneity of the field along z

Along the solenoid axis

\[ B_z = B_0 \left[ 1 + E_2 \left( \frac{z}{a} \right)^2 + E_4 \left( \frac{z}{a} \right)^4 + E_6 \left( \frac{z}{a} \right)^6 + \ldots \right] \]

\[ E_{2n} = \frac{1}{B_0 (2n)!} \frac{d^{2n} B_z}{dz^{2n}} \]

By suitable adjustment of coil shape, one may reduce an error coefficient to zero

This notched solenoid is of sixth order

\[ E_2 = E_4 = 0 \]
A 32 T all-superconducting magnet at NHMFL, US

General guidelines for magnet design

Subdivide the winding into a number of concentric sections to improve the efficiency of superconductor utilization.

All sections take the same current, but each section has its own $J$, $\alpha$ and $\beta$.

Each section operates at the maximum current density allowed by the local field level.
Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 11  Section 5 (Y123)

Wilson
Superconducting Magnets
Chapter 3

Papers cited in the slides