Composition Effects on the Critical Current of MOCVD-processed Zr:GdYBCO Coated Conductors in an Applied Magnetic Field

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Introduction

• $I_c(B)$ of YBCO coated conductors can be modified through
  – Changing composition (RE:Ba:Cu ratios)
  – Rare earth substitution (replacing Y with Gd, Sm)
  – Adding extrinsic defects (Zr, Sn & more being searched)

• There have been many studies on the composition effects for REBCO, but little has been done for Zr:REBCO

• It is crucial to improve the understanding on the interaction between the intrinsic and extrinsic pinning centers
Some of the advancements in understanding

- **RE2O3 precipitates**
  - Lu, Li, Zhao (APL 1992): Y2O3 nanodots are effective pinning for 0T – 7T
  - Wang (J. Appl. Phys. 2006): Y1.1 for optimum Jc(B)
  - Chen, Selva (APL 2009): RE2O3 dots could be assembled to form layers, which were aligned with ab-plane and enhanced pinning in ab-plane
- **BaZrO3 columns**
  - Driscoll (Nature Mat 2004): Zr extrinsic defects, strong pinning along c-axis
  - Goyal (Superc. S&T 2005): nano-columns comprised of BZO dots
  - Yamada (APL 2005): BZO nano-columns through the film thickness
  - Chen, Selva (APL 2009): interaction of bidirectionally aligned defects; explained Jc(B)

- In the present work, we want to improve our understanding of the Interaction between RE2O3 and BZO via investigating the composition effects:
  - Effects of Gd+Y content
  - Effects of Gd to Y ratio
  - Effects of Zr concentrations
Composition Control in MOCVD for Zr:GdYBCO

• Our control is based on the functional relation of the film composition with the precursor composition, deposition temperature and pressure.
• Incorporate rate or film-precursor ratio depends on T and P

For example, precursor $\text{Zr}_{0.065}\text{Gd}_{0.6}\text{Y}_{0.6}\text{Ba}_{2}\text{Cu}_{2.3}$ + Susceptor 965$^\circ$C + Pressure 2.3Torr = film of $\text{Zr}_{0.05}\text{Gd}_{0.6}\text{Y}_{0.6}\text{Ba}_{2}\text{Cu}_{3.3}\text{O}_7$
Effects of Gd+Y content in GdYBCO

Rare-earth rich eliminate Ba-Cu-O phase; enhance pinning.

Aligned RE$_2$O$_3$ dots enhance ab-peak.

Varying Gd+Y in 0.5 μm thick GdYBCO film with Ba=2, Cu=3.3
Gd+Y content dependence of $J_c$(sf), $J_c(1T, //ab)$, $J_c(1T, //c)$, $J_{c_{\text{min}}}(1T, \text{any angle})$

In a wide range of rare-earth content (RE = 1.2 – 1.5), $J_c$ varied not much.

This finding is in contrast to that reported by Wang for PLD YBCO, where $J_c$ dropped dramatically when Y content varying from 1.1 to 1.3.

Gd+Y content dependence for in 0.5 μm thick GdYBCO film with Ba=2, Cu=3.3
Effects of Gd+Y content in Zr:GdYBCO

RE content dependence for 0.5 $\mu$m thick Zr:GdYBCO film with Ba=2, Cu=3.3, Zr=0.055

The c-peak was leveled off completely when RE>1.4.
The a-b peak could also be leveled off under certain conditions.
However, the $J_{c\text{ min}}(B=1T)$ is still about 2 times of that without Zr.
Interaction between vertically aligned BZO columns and horizontally aligned RE$_2$O$_3$ precipitates

RE=1.2 content shows both columnar defects and layers comprised of nano-precipitates

RE=1.5 exhibits only short columnar segments; instead “thicker” precipitates are aligned with ab-planes

TEM cross-sectional images by Dean Miller of ANL
What happened to RE1.1? How was the ab-peak leveled off?

Lacking excess RE?

No. 10% is a large amount. In the case of without Zr addition, the ab-peak constantly stand there.

Under certain growth condition, the well formed BZO nanocolumns penetrating through the film thickness destroyed the horizontal alignment. Thus, the ab-peak was leveled off.
Can the superposition of the curves for low RE and high RE make a flat curve? We can test it. However, it will not result in a higher $J_{c_{\min}}$. We are more interested in seeing the superposition with RE1.2.
In thicker Zr:GdYBCO films

- 4 times-thick film of Zr0.055Gd0.6Y0.6Ba2Cu3.3O7, processed by 4 passes enhanced c-peak

<table>
<thead>
<tr>
<th>B</th>
<th>0</th>
<th>1T, //ab</th>
<th>1T, //c</th>
<th>1T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic (A)</td>
<td>529</td>
<td>241</td>
<td>237</td>
<td>142</td>
</tr>
</tbody>
</table>
In thicker Zr:GdYBCO films

- Alternating composition from pass to pass
- Zr0.06Gd0.75Y0.75Ba2Cu3.3O7 \ Zr0.06Gd0.6Y0.6Ba2Cu3.3O7
- Zr0.06Gd0.75Y0.75Ba2Cu3.3O7 \ Zr0.06Gd0.6Y0.6Ba2Cu3.3O7
- The c-peak is still leveled off

<table>
<thead>
<tr>
<th>B=</th>
<th>0</th>
<th>1T, //ab</th>
<th>1T, //c</th>
<th>1T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic (A)</td>
<td>585</td>
<td>215</td>
<td>167</td>
<td>130</td>
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</table>
Zr concentration effects in Zr:GdYBCO

For Zr-concentration in the range of 0.04 – 0.075, c-peak can be higher than or the same height as ab-peak. $J_c(1T, \text{min})$ also takes its optimum value for Zr-concentration in this range, $\sim 0.8\text{MA/cm}^2$, which is double of the value for GdYBCO without Zr doping.

Zr-concentration dependence of $J_c$ for in 0.5 μm Zr:GdYBCO film with Gd=0.6, Y=0.6, Ba=2, Cu=3.3
Conclusion

• The composition ratio RE:Ba:Cu is the key to effective flux pinning of Zr-inclusions in MOCVD fabricated REBCO films. Over-high RE could suppress or level off c-peak associated with the pinning from BZO nano-columns; Insufficient RE leads to low Ic
• The removal of Jc peak at B//ab could be attributed to broken of horizontal alignment of RE₂O₃ dots by the well-formed BZO columns
• RE content greater than 1.4 could level off the Jc peak at B//c
• For RE content ranging from 1.2 to 1.5, Jc(sf) and Jc_min(77K, 1T) vary little
• The Zr-concentration in the range of 0.025 – 0.075 could be effective pinning centers
• Increasing Gd/Y ratio increased Jc(1T,77K). In self-field or low field, however, the optimized Gd/Y ratio is about 1