Assessment of the $I_c(B, T, \theta)$ characteristics of PLD-GdBCO tape with columnar BaSnO$_3$ nanoprecipitates

M. Lao$^1$, J. Hänisch$^1$, A. Meledin$^2$, A. Molodyk$^3$, V. Chepikov$^3$, S. Lee$^4$, V. Petrykin$^4$
and B. Holzapfel$^1$

INSTITUTE FOR TECHNICAL PHYSICS, SUPERCONDUCTING MATERIALS AND APPLICATIONS

$^1$Institute of Technical Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany
$^2$Central Facility for Electron Microscopy (GFE), RWTH Aachen University, Aachen, Germany
$^3$SuperOx, Moscow, Russia
$^4$SuperOx Japan LLC, Sagamihara, Japan

CCA 2018, Vienna, Austria
Motivation

- To improve in-field performance of coated conductors → artificial pinning centers

SuperOx R&D
- Addition of BaSnO$_3$ and BaZnO$_3$
- Columnar nano-inclusion
- Roughly parallel to the c-axis

Measurement setup

- He gas flow cryostat
  - 4 – 200 K
- Split coil magnet
  - -6 T to 6 T
- Angular rotation around z-axis, minimum step: 0.5°
- Applied current up to 1000 A
- Four point probe technique
- Full-width tapes
- Length: 7-9 cm
- $V(I) = V_c (I/I_c)^N$; $E_c = 0.5 \mu V \text{ cm}^{-1}$
- Maximum Lorentz force

\[ V(I) = V_c (I/I_c)^N; \quad E_c = 0.5 \mu V \text{ cm}^{-1} \]
6-mm wide tapes produced by SuperOx

<table>
<thead>
<tr>
<th>Sample name</th>
<th>APC</th>
<th>Deposition rate (nm/min)</th>
<th>GdBCO thickness (µm)</th>
<th>$T_c$ (K) [1]</th>
<th>$I_{c, sf}$ at 77 K (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>-</td>
<td>750</td>
<td>1.1</td>
<td>93.3</td>
<td>219</td>
</tr>
<tr>
<td>APC-375</td>
<td>6 mol% BaSnO$_3$</td>
<td>375</td>
<td>1.1</td>
<td>91.9</td>
<td>141</td>
</tr>
<tr>
<td>APC-560</td>
<td>6 mol% BaSnO$_3$</td>
<td>560</td>
<td>1.1</td>
<td>91.9</td>
<td>125</td>
</tr>
</tbody>
</table>

The microstructure was investigated using transmission electron microscopy.

Sample TEM results

Diameter of the nanorods: 5-8 nm
Nanoparticles: Gd$_2$O$_3$ and BaSnO$_3$ (BSO)
Short BSO nanorods:
- 40-80 nm in length
- Slightly tilted with respect to the c-axis

Similar pinning landscape with APC-375
Further TEM investigation is ongoing
Results: Field-dependence of \( I_c, H \parallel c \)

- Enhancement in \( I_c \) increases as temperature decreases.
- Largest enhancement around \( \approx 1 \) T, about 40% at 20 K
- **Matching field of 1.3 T** (density of BSO nanorods: 635 \( \mu \text{m}^{-2} \))
Results: Angle dependence of $I_c$

$\mu_0 H_{\text{app}} = 1$ T

- APC samples have smaller $I_c$-anisotropy.
- $ab$-peaks are slightly tilted → sharpest in the reference sample.
- Peak at $+/\pm 10^\circ$: slightly tilted BSO nanorods; at $0^\circ$ in reference sample
  - Prominence decreases at lower temperatures
Results: Angle dependence of $I_c$

$\mu_0 H_{\text{app}} = 5 \, \text{T}$

- Peak due to BSO nanorods is less prominent.
- $ab$-peaks are sharper.
- $I_c$-anisotropy looks similar for the three samples at 20 K.
**$I_c(B)$ analysis**

- Linear behavior in $I_c(B)$ is difficult to distinguish in APC samples.
- $I_c(B) \propto B^{-\alpha}$
- Extraction of $\alpha$ (slope) becomes ambiguous

\[
F_p(B) = F_{p0} \left( \frac{B}{B_{c2}} \right)^p \left( 1 - \frac{B}{B_{c2}} \right)^q
\]

\[
\frac{F_p(B)}{F_{p,\text{max}}} = \frac{p^q}{q^q} \left( \frac{B}{B_{\text{max}}} \right)^p \left( \frac{p + q}{p} - \frac{B}{B_{\text{max}}} \right)^q
\]
\[ \alpha \approx 1 - p \]

- \( p \) can be used as an indicator of pinning center.
- Small defect density: \( n_p \xi^3 \approx 0.12 \times 10^{-3} \)
- Consistent with simulations (GL-theory)
  - BSO-dominates as pinning center (isotropic-like pinning)
  - \( \text{Gd}_2\text{O}_3 \) for the reference sample
Values of $T^*$ are consistent with several published values [1,2].

Weak pinning for $T < 45$ K.

Larger $I_c^{\text{str}}(0)$ indicates contribution of the BSO nanoparticles to strong pinning.

\[ I_c^{\text{str}}(T) = I_c^{\text{str}}(0) \exp \left[ -3 \left( \frac{T}{T^*} \right)^2 \right] \]

\[ I_c^{\text{wk}}(T) = I_c^{\text{wk}}(0) \exp \left( -\frac{T}{T_0} \right) \]

---

<table>
<thead>
<tr>
<th>sample</th>
<th>$T^*$ [K]</th>
<th>$I_c^{\text{str}}(0)$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>85</td>
<td>513</td>
</tr>
<tr>
<td>APC-375</td>
<td>81</td>
<td>706</td>
</tr>
<tr>
<td>APC-560</td>
<td>82</td>
<td>651</td>
</tr>
</tbody>
</table>
Summary

- \( \text{BaSnO}_3 \rightarrow \) short nanorods with matching field of 1.3 T

- Addition of BSO APC \( \rightarrow \) up to 40% enhancement in \( I_c \) at 20 K

- \( I_c \) increase at a wide angular range except near the \( ab \)-plane direction

- Isotropic-like pinning contribution from the short BSO nanorods
  - Consistent with simulation using Ginzburg Landau equations.
Thank you!