Jc anisotropy analysis in YBCO coated conductors: hybrid APC effect and modelling using 3D Time Dependent Ginzburg–Landau Equations

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Issues in Coated Conductor R & D

✓ Critical Current
✓ Anisotropy
✓ Grain Boundary
✓ Homogeneity
✓ AC loss
✓ Mechanical property
✓ Stability
✓ Mass production

http://www.fujikura.co.jp/f-news/1191427_4018.html

http://www.magnet.fsu.edu/mediacenter/publications/
Artificial pinning centers “APCs” — Nanorods

BaZrO$_3$, BaSnO$_3$, Double perovskite, BaHfO$_3$, etc

- **BaZrO$_3$ column**
  - D. Feldmann et al., SUST 23, 095004 (2010)

- **BaSnO$_3$ nanorods**
  - P. Mele et al., SUST 21, 032002 (2008)
  - A. Tsuruta et al., SUST 27, 065001 (2014)
  - C. Varanasi et al., APL 93, 092501 (2008)

- **Ba$_2$YNbO$_6$ nanorods**
  - H. Tobita et al., SUST 25, 062002 (2012)

- **BaHfO$_3$ nanorods**
  - J. Hanisch et al., SUST 19, 534 (2006)
  - A. Tsuruta et al., SUST 27, 065001 (2014)

- **Fpmax = 32.3 GN/m$^3$ at 75 K, B//c**

- **Fpmax = 28.0 GN/m$^3$ at 77K, B//c**
Artificial pinning centers “APCs” — Nanorods

Nanorods

✓ Selection of material and
✓ Straightness of nanorods
✓ Appropriate diameter of nanorods
✓ Sharp interface
✓ High density without Tc suppression

BaZrO₃ column

BaSnO₃ nanorods

Fpmax = 28.3 GN/m³ at 77 K, B//c

Fpmax = 28.0 GN/m³ at 77 K, B//c

D. Feldmann et al., SUST 23, 095004 (2010)
H. Tobita et al., SUST 25, 062002 (2012)
J. Hanisch et al., SUST 19, 534 (2006)
A. Tsuruta et al., SUST 27, 065001 (2014)
Artificial pinning centers — Nanoparticles

Y211, Y2O3, BaZrO3, BaSnO3, etc


Y2O3 particles

Fpmax = 16 GN/m³ at 77 K, B//c

P. Mele et al., SUST 20, 616 (2007)

BaZrO3 particles

Fpmax = 21 GN/m³ at 77 K, B//c

J. Gutierrez et al., Nature Mat. 6, 367 (2007)

BaZrO3 particles

Nanoscale strain

A. Llordes et al., Nature Mat. 11, 329 (2012)

BaZrO3

M. Miura et al., SUST 26, 035008 (2013)
Artificial pinning centers — Nanoparticles

✓ Selection of material and
✓ Appropriate diameter of nanoparticles
✓ High density without Tc suppression
✓ Sharp interface
✓ Surrounding additional defects

Y211 particles

Y$_2$O$_3$ particles

F$_{\text{pmax}}$ = 16 GN/m$^3$ at 77 K, B//c

J. Gutierrez et al., Nature Mat. 6, 367 (2007)

A. Llordes et al., Nature Mat. 11, 329 (2012)

M. Miura et al., SUST 26, 035008 (2013)
Advanced APC structures—Hybrid, MLs, segmentation

**Hybrid APCs**

- **BaZrO$_3$ nanorods**
- **BaZrO$_3$ + Y$_2$O$_3**
- **Y$_2$O$_3$ particles**

P. Mele et al., SUST 21, 015019 (2008)

**MLs + Segmentation**

- Weak point disorder (vortex glass)
- Pinning strengths
- Spacing
- Aspect ratio
- Spacing
- C-axis correlated disorder (Droste glass)

T. Horide et al., APL 92, 182511 (2008)

**Segmentation**

B. Maiorov et al., Nature Mat. 8, 398 (2009)

**MLs**

G. Ercolano et al., SUST 24, 095012 (2011)

F$_{\text{pmax}}$ = 26 GN/m$^3$ at 77 K, B//c

**(Nb-Ta)YBCO**

Advanced APC structures-Hybrid, MLs, segmentation

- Structural design
- Tuning of crystal growth
- Combination of pinning centers

- Kiessling et al., SUST 24, 055018 (2011)
- Ercolano et al., SUST 24, 095012 (2011)
- Maiorov et al., Nature Mat. 8, 398 (2009)
- Mele et al., SUST 21, 015019 (2008)
- Horide et al., APL 92, 182511 (2008)
- (Nb-Ta)YBCO
  - $F_{\text{pmax}} = 26 \text{ GN/m}^3$ at 77 K, $B//c$
Understanding and Control of $J_c$ angular dependence

✓ $J_c$ measurement in the films with APCs
✓ 3D Time Dependent Ginzburg-Landau Equations
✓ Theoretical modeling of $J_c$-$\theta$ characteristics
Incorporation of hybrid APCs

YBCO+BSO Mixed target with \( Y_2O_3 \) sector

BSO: 2wt%, 4wt%
\( Y_2O_3 \): 0.7 areal%, 2.4 areal%

BSO nanorods and \( Y_2O_3 \) nanoparticles were successfully incorporated in YBCO films
- In YBCO+BSO(4), c-axis peaks were observed regardless of magnetic field, but the peak became small in high magnetic field.
- In hybrid APCs, Jc near θ=135° was improved by Y₂O₃ nanoparticles, and isotropic Jc was obtained at 1 T in YBCO+BSO(2)+Y₂O₃(2.4).
$J_c \theta$ modelling in YBCO films

\begin{align*}
B//c \\
\text{YBCO+BSO} & \\
\text{BSO} & \text{nanorod} \\
\text{Tilted field} \\
\text{YBCO+BSO} & \\
\text{Oxygen} & \text{vacancy} \\
\text{YBCO+BSO} & \text{+} \text{Y}_2\text{O}_3 \\
\text{Y}_2\text{O}_3 & \text{nanoparticle}
\end{align*}

\begin{align*}
J_c & = 22 \text{ MA/cm}^2 \\
J_c & = 0.0047 \text{ MA/cm}^2 \\
J_c & = 0.90 \text{ MA/cm}^2
\end{align*}

\begin{align*}
f_{p, \text{nanorod}} & = \pi \xi_{ab}^2 \times L \times \frac{B_c^2}{2\mu_0} \times \frac{1}{\xi_{ab}} \\
J_c & = \frac{f_{p, \text{nanorod}}}{\phi_0 L} \\
J_c & = \frac{f_{p, \text{nanorod}}}{\phi_0 L}
\end{align*}

\begin{align*}
f_{p, \text{vacancy}} & = \frac{\pi D^2}{4} \times \xi_{ab0} \times \frac{B_c^2}{2\mu_0} \times \frac{1}{\xi_{ab}} \\
F_{p, \text{vacancy}} & = f_{p, \text{vacancy}} \sqrt{n \times \xi_{ab}^2 d} \\
J_c & = \frac{F_{p, \text{vacancy}}}{\phi_0 d} \\
J_c & = \frac{F_{p, \text{vacancy}}}{\phi_0 d}
\end{align*}

\begin{align*}
f_{p, \text{nanoparticle}} & = \pi \xi_{ab} \xi_c \times 2r \times \frac{B_c^2}{2\mu_0} \times \frac{1}{r} \\
J_c & = \frac{f_{p, \text{nanoparticle}}}{\phi_0 d} \\
J_c & = \frac{f_{p, \text{nanoparticle}}}{\phi_0 d}
\end{align*}
### Jc analysis assuming staircase vortices

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Calculated $J_c$</th>
<th>Experimental data $J_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>YBCO+BSO, B∥c BSO Nanorod</td>
<td>22 MA/cm²</td>
<td>&gt;&gt; 1-3 MA/cm² (YBCO+BSO)</td>
</tr>
<tr>
<td>YBCO+BSO, tilted field Oxygen Vacancy</td>
<td>0.0047 MA/cm²</td>
<td>&lt;&lt; 0.28 MA/cm² (pure YBCO)</td>
</tr>
<tr>
<td>YBCO+BSO+$Y_2O_3$, tilted field nanoparticle</td>
<td>0.90 MA/cm²</td>
<td>~ 0.46 MA/cm² (YBCO+$Y_2O_3$)</td>
</tr>
</tbody>
</table>

- In YBCO+BSO, Vortices moves by forming double kink or half loop.
- When dominant pinning center is oxygen vacancies in YBCO+BSO for tilted magnetic field, not only vortex pinning, but also magnetic interaction and line tension determine $J_c-\theta$.
- In YBCO+BSO+$Y_2O_3$ films, $Y_2O_3$ nanoparticles determine $J_c-\theta$ when magnetic field is tilted from the c-axis.
- These indicate staircase vortex configuration.
Type II superconductor – Abrikosov lattice

- Bitter pattern
- STM
- Lorentz microscopy
- MO


- Quantized vortex (1957)

Abrikosov
Time Dependent Ginzburg–Landau Equations

✓ Langevin equation

$$\frac{\partial}{\partial t} \psi(\mathbf{r}, t) = -L \frac{\delta F}{\delta \psi} + \theta(\mathbf{r}, t)$$

✓ Time dependent Ginzburg- Landau equations

$$\frac{\hbar^2}{2m_s} \left( \frac{\partial}{\partial t} + i \frac{e_s}{\hbar} \Phi \right) \psi = \frac{\hbar^2}{2m_s} \left( \nabla - i \frac{e_s}{\hbar} \right)^2 \psi + \alpha |\psi| - \beta |\psi|^2 \psi$$

$$\frac{1}{\mu_0} \nabla \times (\nabla \times A - \mu_0 H) = j_s + j_n$$

$$j_s = \frac{\hbar e_s}{2m_s D} (\psi^* \nabla \psi - \psi \nabla \psi^*) - \frac{e_s^2}{m_s} |\psi|^2 A$$

$$j_n = \sigma \left( -\nabla \Phi - \frac{\partial A}{\partial t} \right)$$

R. Kato et al., PRB (1993)
M. Machida et al., PRL (1993)
Q. Du et al., PRB (1995)
G. Crabtree et al., PRB (2000)
T. Winiecki et al., PRB (2002)
Vortex anisotropies and 3D TDGL simulation

✓ Line tension energy

\[ \tilde{\varepsilon}_1 \approx \frac{1}{\gamma^2} \varepsilon_1 = \frac{\Phi_0^2}{4\pi\mu_0\lambda_c^2} \ln \kappa \quad \text{for anisotropic} \]

\[ \varepsilon_1 \approx \frac{\Phi_0^2}{4\pi\mu_0\lambda_{ab}^2} \ln \kappa \quad \text{for isotropic} \]

\[ \left( \frac{m_c}{m_{ab}} \right)^{1/2} = \frac{\tilde{\xi}_{ab}}{\tilde{\xi}_c} = \frac{\lambda_c}{\lambda_{ab}} = \gamma \approx 5 - 7 \quad \text{for YBCO} \]

\[ \tilde{\varepsilon}_1 \ll \varepsilon_1 \]

✓ GL equation for the anisotropic case

\[ \frac{\delta F}{\delta \psi} = \alpha \psi + \beta |\psi|^2 \psi - \frac{\hbar^2}{2} \left( \nabla - i \frac{e_s}{\hbar} A \right) \cdot m^{-1} \cdot \left( \nabla - i \frac{e_s}{\hbar} A \right) \psi \]

\[ \frac{1}{m_{ab}}, \frac{1}{m_{ab}}, \frac{1}{m_c} \]
Flux pinning by $c$-axis correlated columnar defects

$\gamma = 7, \ T/T_c = 0.4, \ B/B_c = 0.3, \ \theta = 45^\circ, \ k = 20$
Vortex staircase in anisotropic superconductors

\[ T/T_c = 0.4, \quad B/B_{c2} = 0.3, \quad \theta = 45^\circ, \quad k = 20 \]

\[ \gamma = 1 \quad \text{and} \quad \gamma = 7 \]

\[ \varepsilon_1 \approx \frac{\Phi_0^2}{4\pi\mu_0\lambda_{ab}^2} \ln \kappa \]

\[ \tilde{\varepsilon}_1 \approx \frac{1}{\gamma^2 \varepsilon_1} \]
Anisotropic $J_c$ behaviors due to staircase vortices

Angular dependence of vortex configuration (pinned, staircase, unpinned) strongly affects $J_c - \theta$ characteristics.
Angular dependent $J_c(\theta)$ in YBCO with nanorods

Critical current density (MA/cm²) 77 K, 1 T, SC STO

77 K, 1 T, SC STO

YBCO-3%BSO $T_c = 88$ K

Pure YBCO $T_c = 90$ K
Trapping angle

- Trapping angle $=(2U/\varepsilon)^{1/2}$
- For tilted magnetic field, nanoparticle incorporation in addition to nanorods is very effective.
- When field angle is larger than trapping angle, nanorods do not work as pinning centers.
Summary

✓ Recent progress in flux pinning APCs was discussed.

✓ $J_c \theta$ characteristics were measured in YBCO films with hybrid APCs of BSO nanorods and $Y_2O_3$ nanoparticles.

✓ 3D TDGL equation clarified vortex configuration in tilted magnetic field.

✓ Vortex configuration was discussed by considering vortex energy of magnetic interaction, pinning potential, and line tension.