Probing the Effect of Interface on Pinning Efficiency of 1D BaZrO$_3$ and BaHfO$_3$ Artificial Pinning Centers in YBa$_2$Cu$_3$O$_{7-x}$ Thin Films

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Artificial Pinning Centers (APCs)—for high $J_c$ without H-orientation dependence

Exciting progress has been made in \textit{strain mediated self-assembly} of APCs with different morphology

- 1D APCs provide strong correlated pinning shown as a $J_c$ peak at $H//c$-axis
- Accommodation field $H^*$ can be estimated from 1D APC areal density

Superconductor Science and Technology

Focus on Artificial Pinning Centers in Superconductors

Guest Editors

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Scope

Flux pinning of quantized magnetic vortices is well understood to be a critical function needed in practical superconducting materials, to enable high critical current densities ($I_c$) at high applied magnetic fields up to a few tens of Tesla for many applications (generators, transformers, large magnets,...). For type II superconductors, the flux pinning force density is related to the density, size and dimensionality of the defects generated. Therefore, novel methods of introducing artificial pinning centers (APCs) are required.

2018

http://iopscience.iop.org/journal/0953-2048/page/Focus-on-Artificial-Pinning-Centers-in-Superconductors
Controlling self-assembly of APCs in APC/HTS nanocomposites

Specific questions:

• **Morphology**: What impurity materials will form aligned nanorods (1D APCs) or nanosheets (2D APCs) and nanoparticles (3D APCs) in YBCO matrix?
• **Dimension**: What determines the dimension of the APCs?
• **Orientation**: What determines APC orientations? Is it possible to obtain mixed orientations from the same dopant?
• **Mixed APCs**: 3D pinning landscape via control of each types of APCs? (by APC doping, vicinal double doping)
• **Pinning Efficiency of 1D APCs**: Understanding the effect of APC/YBCO interface on the individual pinning efficiency
1D APC/RE-123 nanocomposites

Oxygen deficient column around the BZO 1D APC due to the defective, semi-coherent APC/YBCO interface


Controlling parameters in APC self-assembly:

- Lattice mismatch at the interfaces (three shown)
- Elastic properties of both APCs and RE-123

- Shi and Wu, Philosophic Magazine 92, 2911 (2012); 92, 4205 (2012);
- Wu and Shi, SUST 30, 103002 (2017) in SUST Special Issue on Artificial Pinning Centers
Elastic Strain Model + Experiment
Understanding & controlling self-assembly of artificial pinning centers

**APC material selection**
APC morphology can be pre-screened based on their elastic properties & lattice constants

**APC dimension**
1D APC diameter is determined by the inverse strain decay length $\lambda_1(2)$

**Mixed APCs**
Configurations of APCs can be tuned by both APC doping, YBCO matrix strain, and double doping

Shi and Wu, *Philosophic Magazine* 92, 2911 (2012); 92, 4205 (2012)


Wu and Shi, in *SUST* Special Issue on Artificial Pinning Centers (2017), Vol. 30, 103002 (2017)
Mixed 1D+2D APCs

APCs of mixed morphologies can be generated from the same APC material.
Local + Global strains: splay around c-axis and switch from c to ab orientation of BaZrO$_3$ and BaSnO$_3$ nanorods

Benefits of mixed 1D+2D APCs: enhanced $J_c$

Overall enhanced $J_c$ in all H directions in mixed BZO (BSO) APC/YBCO possibly due to 1) reduced strain on YBCO; 2) mixed orientations of BZO APCs

Difficult to obtain mixed 1D+2D APCs

Wu et al., SUST 28, 125009(2015)
Mixed 1D+2D+3D APCs

3D APCs add only local perturbation of the strain field
Rigidity of 1D APCs matters—tuning APC morphology using double doping (DD)

1D APCs with higher rigidity:
BSO + Y2O3:
1D + 3D APCs


1D APCs with lower rigidity:
BHO (BZO) + Y2O3:
1D + 2D + 3D APCs


2 vol% BHO + 3 vol% Y$_2$O$_3$

4 vol% BHO + 3 vol% Y$_2$O$_3$

6 vol% BHO + 3 vol% Y$_2$O$_3$

1D+2D+3D Mixed APCs

B. Gautam et al., *AIP Advances*, 7 (7), 0753082017; Gautam et al., SUST 31, 025008 (2017)
Low rigidity of BHO 1D APCs allow mixed 1D+2D+3D APCs to be obtained via double doping for reduced $J_c$ anisotropy

B. Gautam et al., AIP Advances, 7 (7), 075308 (2017); Gautam et al., SUST 31, 025008 (2017); Chen et al., IEEE Trans. Appl. Supercond. 27 (4), 4-8 (2017); SUST 30, 125011 (2017)
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Pinning efficiency of 1D APCs

Questions:
Do all APCs generated contribute to pinning?
What determines their pinning efficiency?

Evaluation of 1D APC pinning efficiency

$H^*$ -- TEM determined accommodation field
$H_{\text{max}}$ -- location of the $F_p$ maximum
$H_{\text{max}}/H^*$ -- proportion of activated 1D APCs

$F_p(H) = J_c x H$ — pinning force density
$F_{p,\text{max}}$ — the maximum value of $F_p$
BZO and BHO form c-axis aligned 1D APCs of comparable diameters of ~5-6 nm in YBCO matrix
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$T_c$ (K)</th>
<th>C-axis lattice constant (Å)</th>
<th>FWHM of YBCO (005) peak</th>
<th>D (nm)</th>
<th>d (nm)</th>
<th>$H^*$ (T)</th>
<th>Lattice mismatch with c-axis of YBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 vol.% BZO/YBCO</td>
<td>89.27</td>
<td>11.82</td>
<td>0.35</td>
<td>5.2</td>
<td>20</td>
<td>5.0</td>
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</tr>
<tr>
<td>4 vol.% BZO/YBCO</td>
<td>87.48</td>
<td>11.71</td>
<td>0.34</td>
<td>5.8</td>
<td>15</td>
<td>9.2</td>
<td>7.7%</td>
</tr>
<tr>
<td>6 vol.% BZO/YBCO</td>
<td>86.90</td>
<td>11.67</td>
<td>0.27</td>
<td>5.9</td>
<td>12</td>
<td>14.3</td>
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<tr>
<td>2 vol.% BHO/YBCO</td>
<td>88.85</td>
<td>11.77</td>
<td>0.42</td>
<td>5.0</td>
<td>30</td>
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</tr>
<tr>
<td>4 vol.% BHO/YBCO</td>
<td>85.84</td>
<td>11.77</td>
<td>0.51</td>
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<td>13</td>
<td>12.2</td>
<td>7.1%</td>
</tr>
<tr>
<td>6 vol.% BHO/YBCO</td>
<td>78.50</td>
<td>11.78</td>
<td>0.49</td>
<td>5.0</td>
<td>16</td>
<td>8.0</td>
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</tbody>
</table>

- $H^*$ increases with BZO doping linearly while a nonlinear relationship is seen with BHO doping
- More defective BZO 1D APC/YBCO interface is hinted by the reduction of the c-axis lattice constant
- A more coherent BHO/YBCO interface is favorable for high pinning efficiency
Two co-axial columns around a BZO 1D APC:
- one is further away from the 1D APC with lower $T_{c1} < T_c$ due to the tensile strain on the c-axis of YBCO
- the other is immediately around the APC with minimal strain due to defects formation with even lower $T_{c2} < T_{c1} < T_c$ that affects pinning efficiency of the 1D APCs much more.
• Semi-coherent BZO 1D APC/YBCO interface
• Coherent BHO 1D APC/YBCO interface is maintained up to 6 vol.% BHO doping
Semi-coherent BZO 1D APC/YBCO interface becomes more defective with increasing BZO doping, resulting reduction of the $J_c(H)$ and $F_p(H)$.

Coherent BHO 1D APC/YBCO interface sustains in 2-6 vol.%, while the best $J_c(H)$ and $F_p(H)$ are observed at 4 vol.%. 

- Semi-coherent BZO 1D APC/YBCO interface becomes more defective with increasing BZO doping, resulting reduction of the $J_c(H)$ and $F_p(H)$
- Coherent BHO 1D APC/YBCO interface sustains in 2-6 vol.%, while the best $J_c(H)$ and $F_p(H)$ are observed at 4 vol.%
Coherent APC/YBCO interface leads to higher pinning efficiency

Semi-coherent APC/YBCO interface leads to lower pinning efficiency

$F_p > 180$ GN/m$^3$ is the highest so far reported at 65 K.

BZO 1D APC: $H_{\text{max}} \sim 5T$ (H$^* \sim 9.2T$)
BHO 1D APC: $H_{\text{max}} > 9T$ (H$^* \sim 12.2T$)

B. Gautam et al., submitted; V. Ojigunmi et al., submitted
**H* -- TEM determined accommodation field**

**H_{max} -- location of the F_p maximum**

**H_{max}/H* -- proportion of activated 1D APCs**

**BZO 1D APC:** $H_{max}/H* < 0.7$ in 2-6 vol.% BZO doping, indicating a large portion of inactive BZO 1D APCs.

**BHO 1D APC:** $H_{max}/H*$ up to 3.5, more room to improve?
Jc(\theta) of 4% BZO, BHO SD and YBCO films

\[ J_c (A/cm^2) \]

- 77 K and 1.0 T
- 77 K and 3.0 T
- 65 K and 5.0 T
- 65 K and 9.0 T

black-BZO/YBCO
red-BHO/YBCO
blue-YBCO

Invited presentation 1MO1C-01 was given at ASC 2018, October 28-November 02, 2018, Seattle (USA).
Summary

- Understanding the Interfacial strains (local and global) provides means to control APC’s morphology, orientation and dimension.

- The mixed APCs (1D+2D+3D) provide benefits of strong and isotropic pinning

- 1D APC/YBCO interface plays a key role in determining the APC pinning efficiency as reflected in the values of the $F_p(H)$, $F_{p,max}$, $H_{max}$, $H_{max}/H^*$

- With coherent BHO 1D APC/YBCO interface, we have obtained $F_{p,max}>180$ GN/m$^3$ and $H_{max}/H$ up to ~3 at 65 K