IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
Invited presentation M3OrC-01 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).

9-13 July 2017
Monona Terrace Community and Convention Center

Interactive approach towards controllable generation of strong and isotropic artificial pinning centers in RE-123 films

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Sponsored by NSF and AFOSR

Outline of this talk

Introduction

- Effect of interfacial strain on the self-assembly of artificial pinning centers (APCs)
- Quantitatively explain, predict and control APCs (morphology, dimension, orientation, etc.)

Development of mixed APCs in YBCO

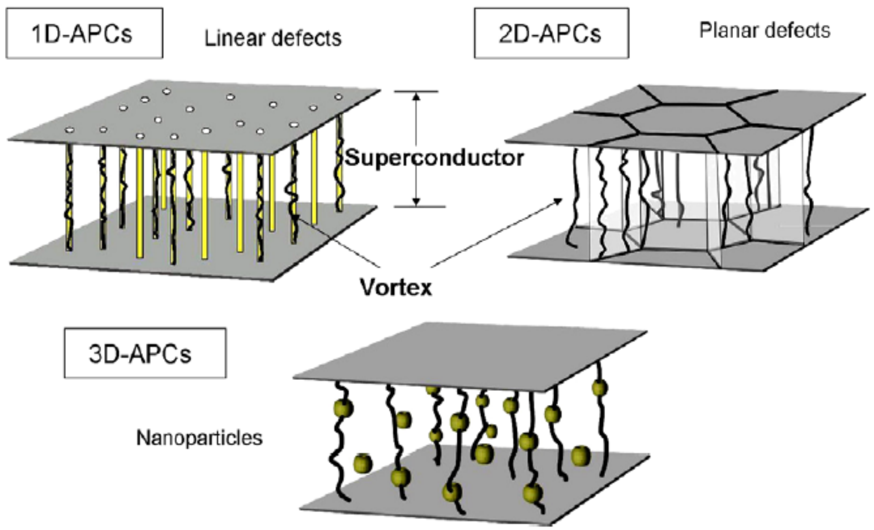
- Vicinal + BZO (BSO) variable concentrations
- Y_2O_3 +BZO (BHO) variable concentrations

Summery

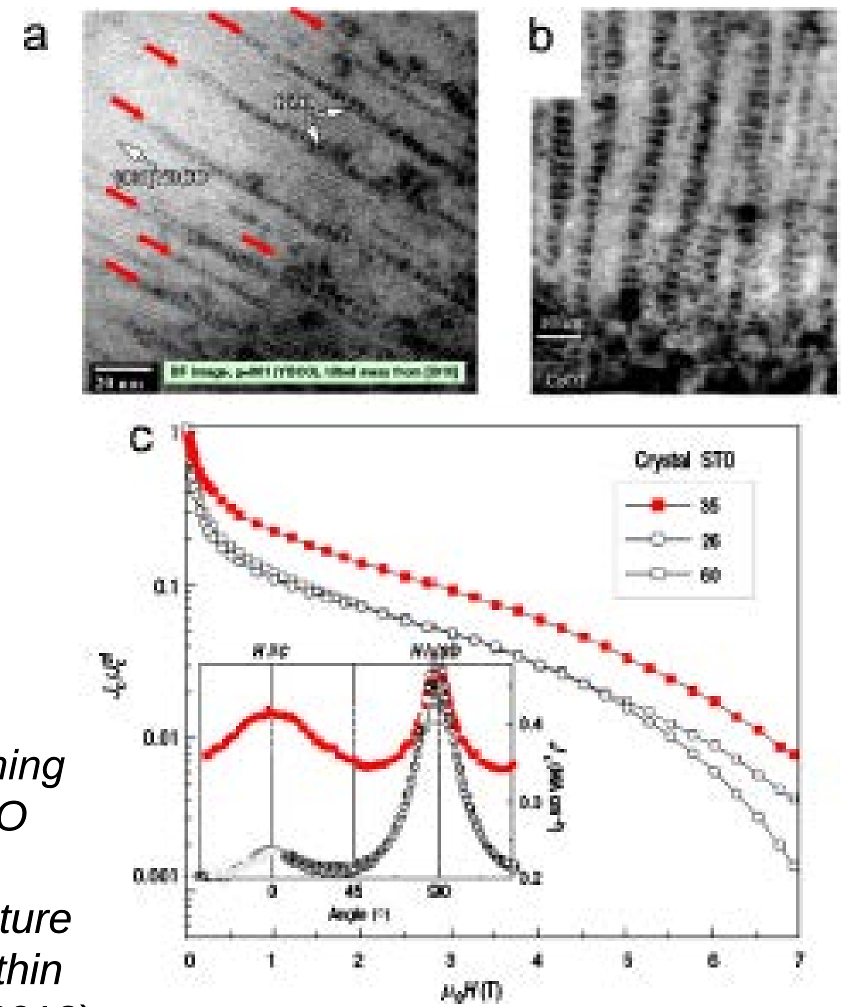
Goal: strong and isotropic pinning

Artificial Pinning Centers (APCs) in RE-123

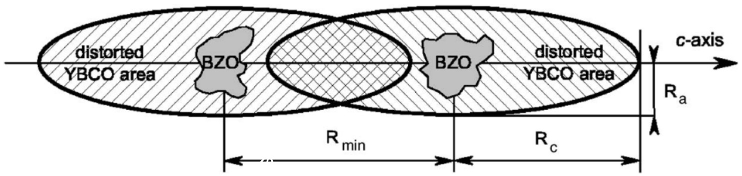
Exciting progress has been made in generation of APCs using in situ and ex situ approaches



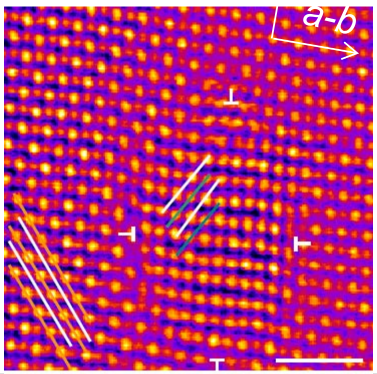
Matsumoto and Mele, topical review on *Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors*, SUST 23 (2010) 014001;
Obradors et al., topical review on *Growth, nanostructure and vortex pinning in superconducting YBa2Cu3O7 thin films based on trifluoroacetate solutions*, SUST 25 (2012) 123001

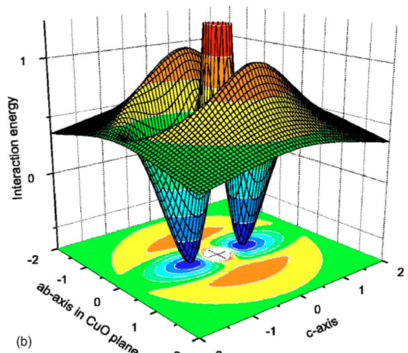


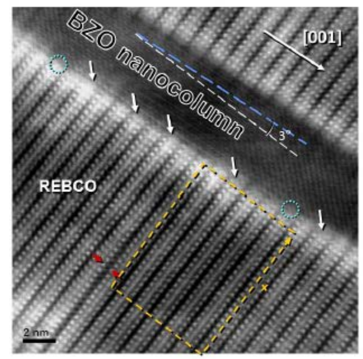
Strain-mediated self-assembly of APCs *in situ* epitaxial APC/YBCO nanocomposites: Interfacial Strain Effect

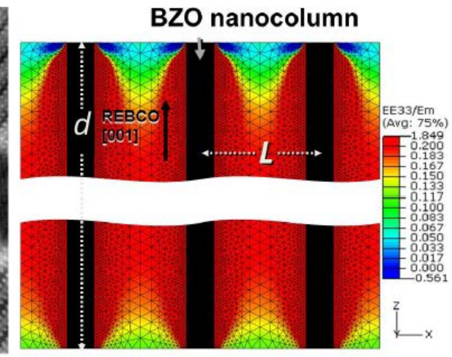


Oxygen deficient column around the BZO/YBCO strained interface-semi-coherent









S. Kang et al. *Supercond Sci Technol*. **18**, 1553 (2005).

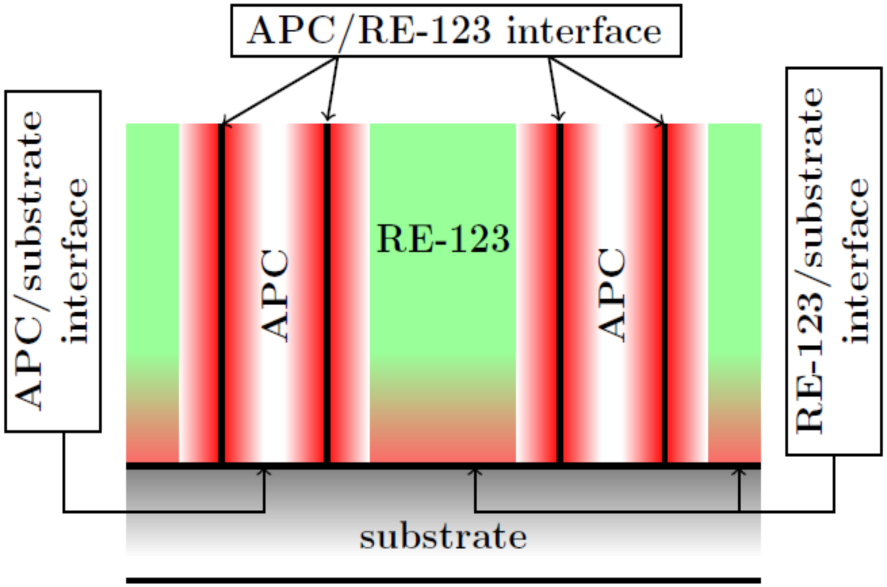
M. Peurla et al., *Phys . Rev. Lett.* **75**, 184524 (2007).

C. Cantoni et al., *ACS Nano* **6**, 4783 (2011).

Two kinds of strained interfaces involved in self-assembly:

- **Dopant/YBCO matrix interface (two different kinds may exist in double doping case)—local**
- **YBCO matrix/substrate interface—global**

Epi APC/RE-123 nanocomposites



Controlling parameters:

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

Shi and Wu, *Philosophical Magazine* **92**, 2911 (2012); ***92**, 4205* (2012);
Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017) ASAP

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Understanding the Interplay of strains is important towards controlling APCs

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 their orientations? Is it possible to obtain mixed orientations from the same dopant?
- **Mixed APCs:** 3D pinning landscape via control of each types of APCs?

Approaches:

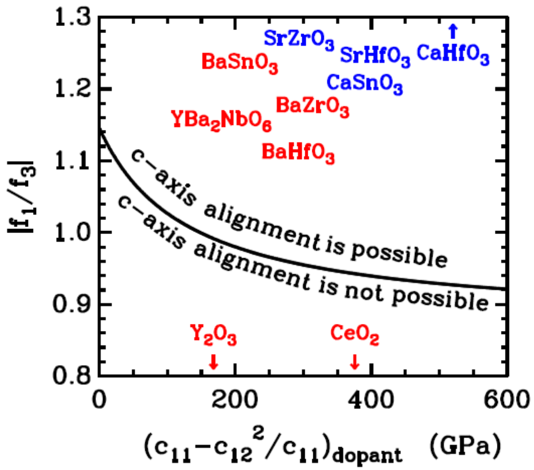
Modeling + fabrication + characterization

Elastic Strain Model + Experiment

Understanding & controlling self-assembly of artificial pinning centers

APC material selection

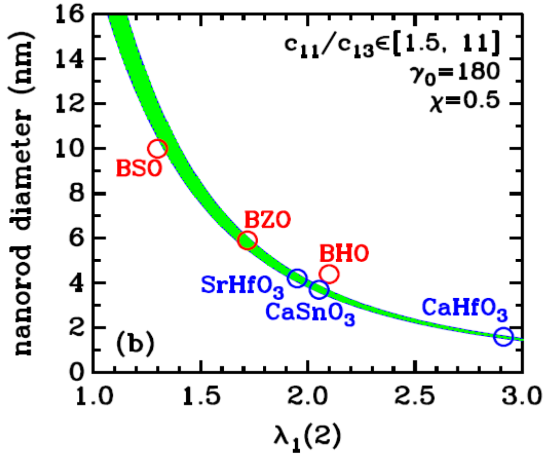
APC morphology can be pre-screened based on their elastic properties & lattice constants



Shi and Wu, *Philosophical Magazine* **92**, 2911 (2012); ***92**, 4205* (2012); Wu and Shi, SUST Special Issue on Artificial Pinning Centers (2017) ASAP

APC dimension

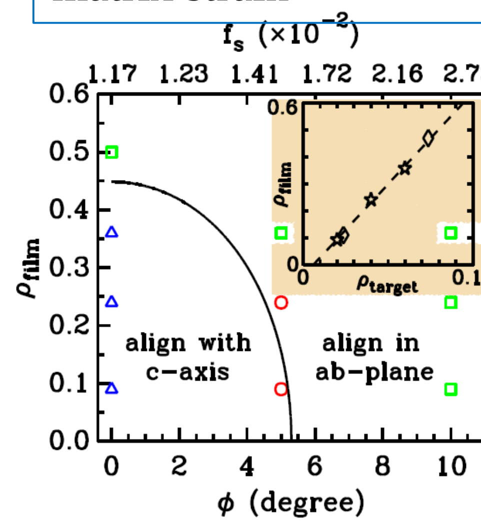
Nanorod diameter is determined by the inverse strain decay length $\lambda_1(2)$



J. Wu et al., *SUST*, 27, 044010 (2014); Shi and Wu, JAP 118, 164301 (2015).

APC orientations

Configurations of APCs can be tuned by both APC concentration and YBCO matrix strain



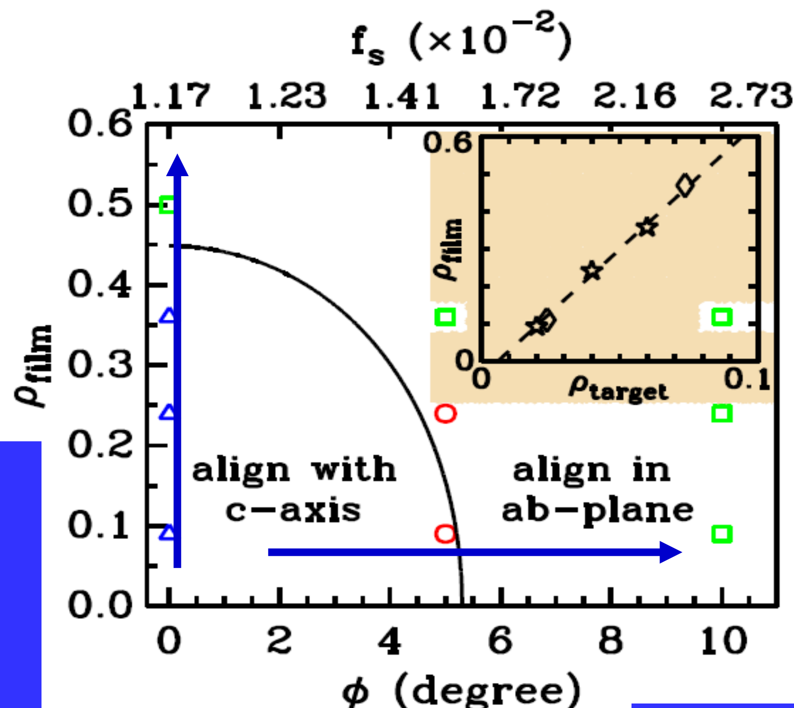
F.J. Baca et al., Advanced Functional Materials 23, 4628, (2013); J. Wu et al., *IEEE Trans. Applied Superconductivity* **25** (3), 1-5 (2015); Wu et al., SUST 28, 125009(2015)

APC orientation vs. YBCO matrix strain

(controlled by APC concentration and film/substrate lattice mismatch)

Switch of 1D APC orientation

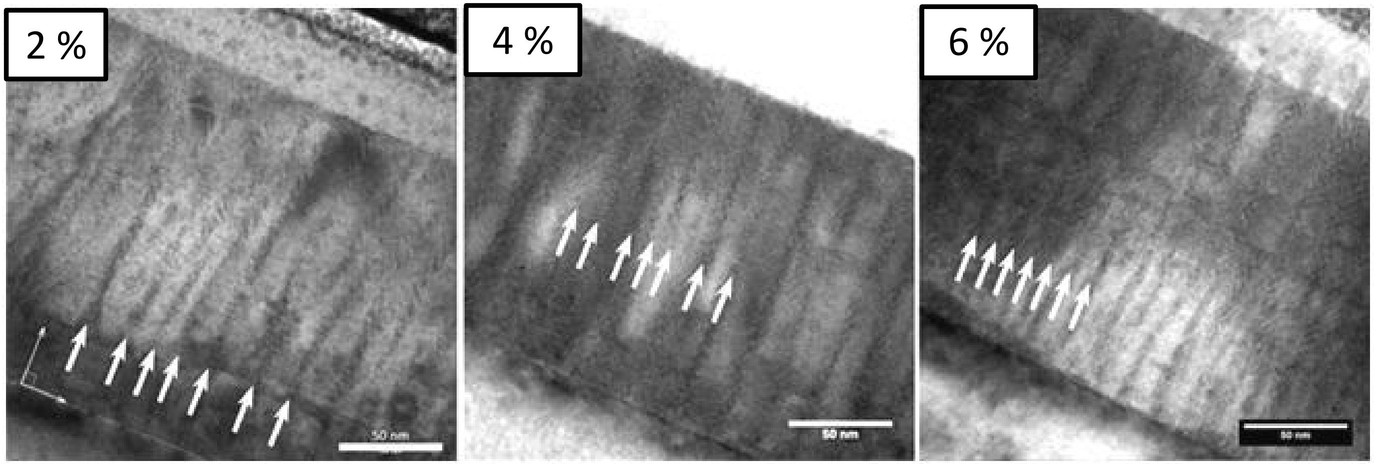
1D APC switch from c-aligned to ab-aligned at high APC concentrations



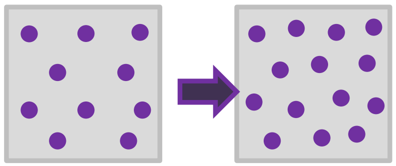
Switch of 1D APC orientation

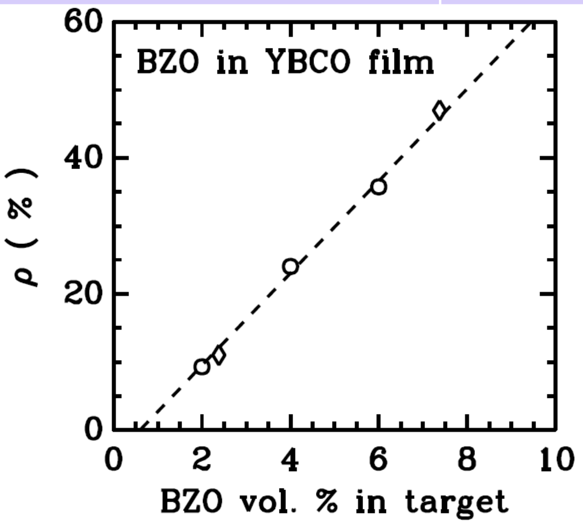
1D APC switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

Shi and Wu, *Phil. Magazine* **92**, 2911 (2012); ***92**, 4205* (2012).
F.J. Baca et al., *Adv. Funct. Mat.* **23**, 4628, (2013);
J. Wu et al., *IEEE Trans. Applied Supercond.* **25**, 1-5 (2015);
J. Wu et al., SUST 28, 125009 (2015).
J.Z. Wu, Endless Quests -- Theory, Experiment and Application of Frontiers of Superconductivity, Peking University Press (2016).



BZO vol. concentration	*2%*	*4%*	*6%*
Nanorod spacing (nm)	10.8 ± 3.2 nm	6.0 ± 2.7 nm	4.4 ± 0.7 nm
Nanorod diameter (nm)	5.2 ± 0.5 nm	5.8 ± 0.6 nm	5.9 ± 0.9 nm





Overlap of the strained matrix around BZO nanorods occurs at around ρ~45% volume portion

- Wu, Judy; Shi, Jack, Baca, Javier; Emergo, Rose; Wilt, Jamie; Haugan, Timothy, “Controlling BZO Nanostructure Orientation in YBCO Films for Three-Dimensional Pinning Landscape”, Supercond. Sci. Technol, **28**, 125009 (2015).

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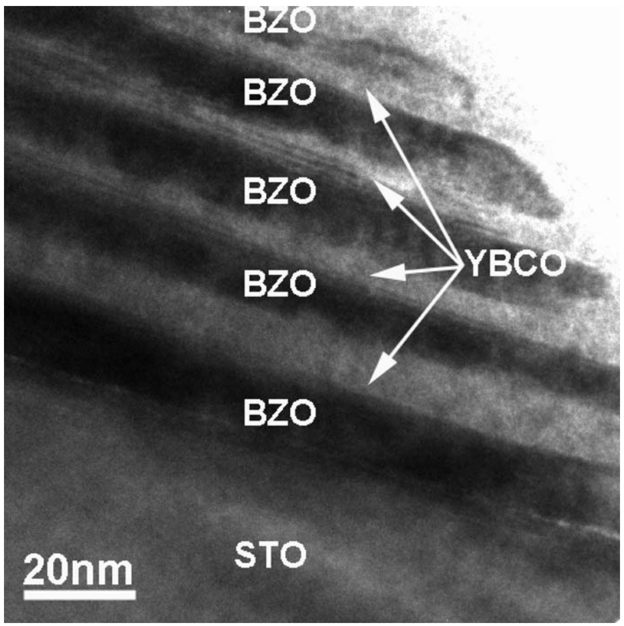
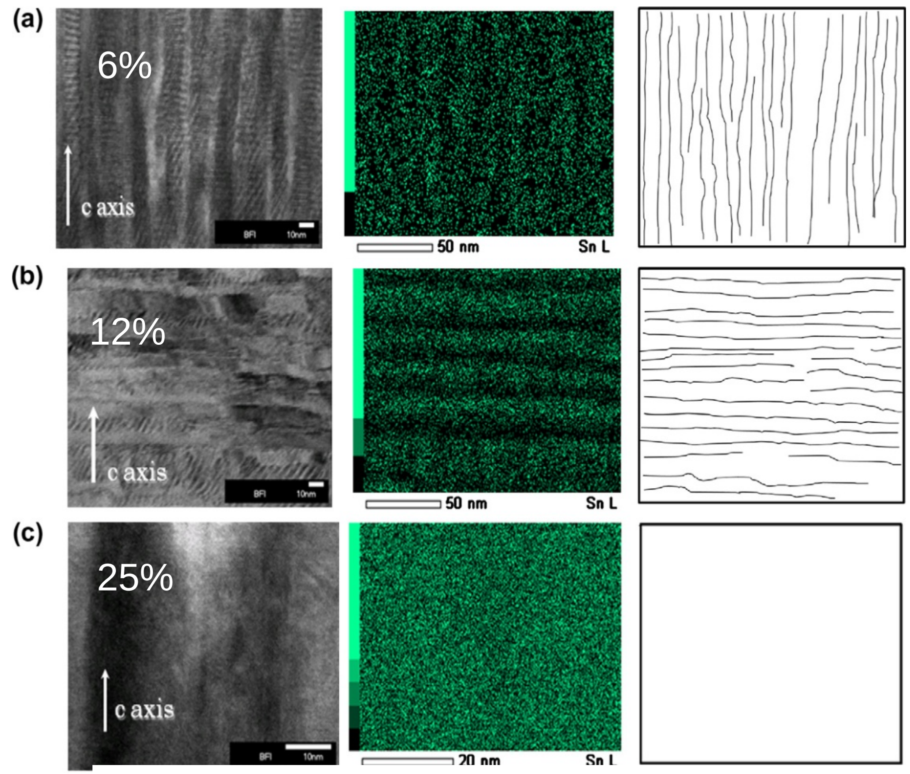
Alignment switch at higher doping levels (nonvicinal)

YBCO:BZO=50%:50%



H. Yang et al., APL 106, 093914 (2009)

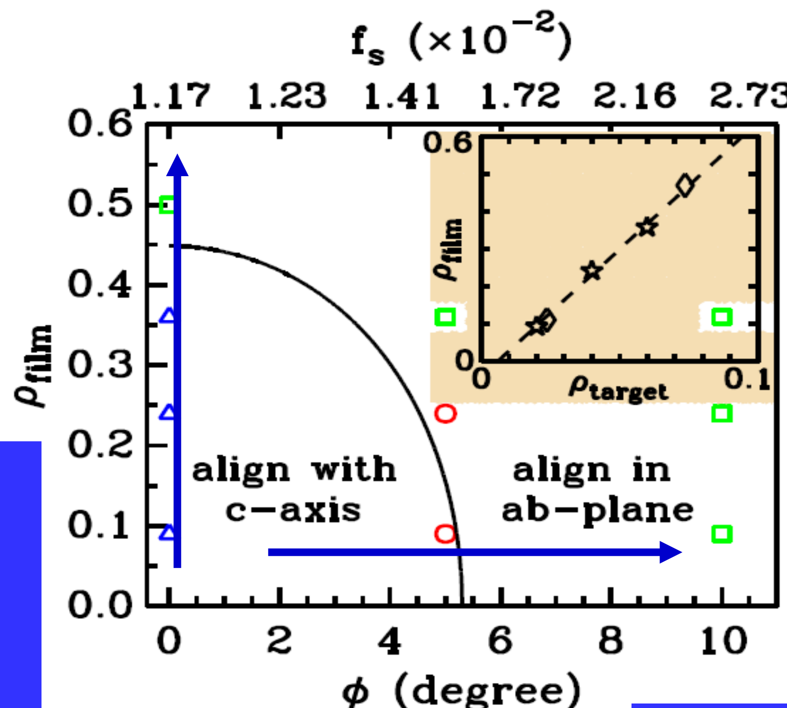
BSO doping (Vol%) in YBCO



S. Nagao et al., Physica C 470, 1304 (2010)

A switch of BZO and BSO nanorods from c-align to ab-align occurs at large doping level

APC orientation vs. YBCO matrix strain
(controlled by APC concentration and film/substrate lattice mismatch)



Switch of 1D APC orientation

1D APC switch from c-aligned to ab-aligned at high APC concentrations

Switch of 1D APC orientation

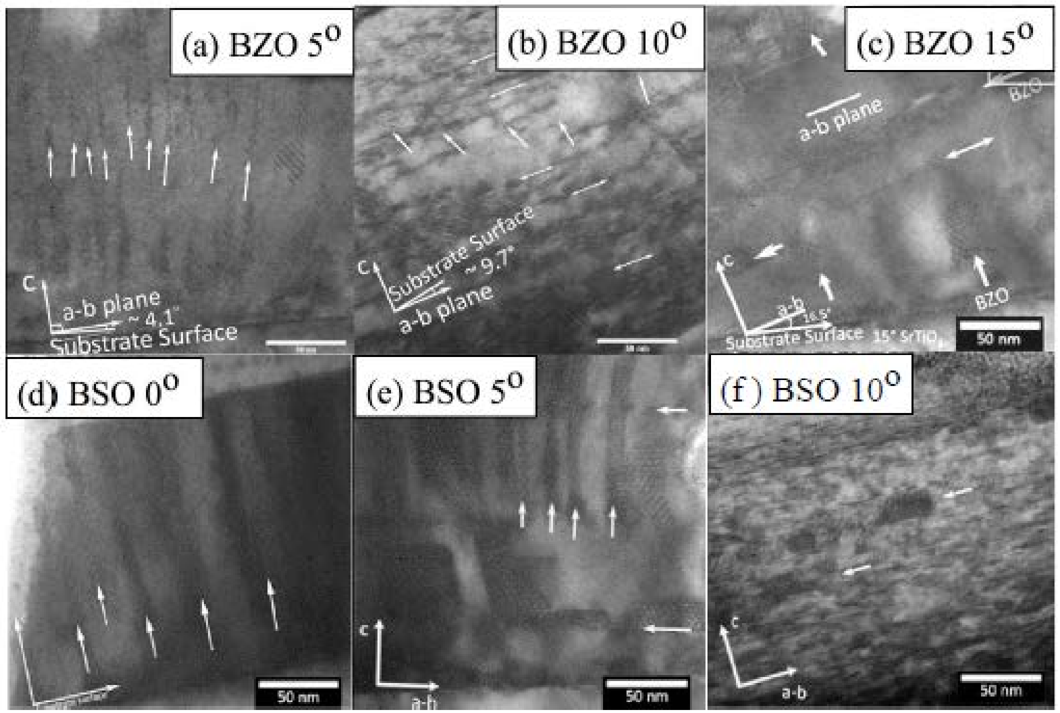
1D APC switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

Shi and Wu, *Phil. Magazine* **92**, 2911 (2012); ***92**, 4205* (2012).
F.J. Baca et al., *Adv. Funct. Mat.* **23**, 4628, (2013);
J. Wu et al., *IEEE Trans. Applied Supercond.* **25**, 1-5 (2015);
J. Wu et al., SUST 28, 125009 (2015).
J.Z. Wu, Endless Quests -- Theory, Experiment and Application of Frontiers of Superconductivity, Peking University Press (2016).

Local + Global strains: splay around c-axis and switch from c- to ab-aligned of $BaZrO_3$ and $BaSnO_3$ APCs

BZO doping

BSO doping



Tensile strain in c-axis

Transition zone with mixed orientations of APCs

Compressive strain in c-axis

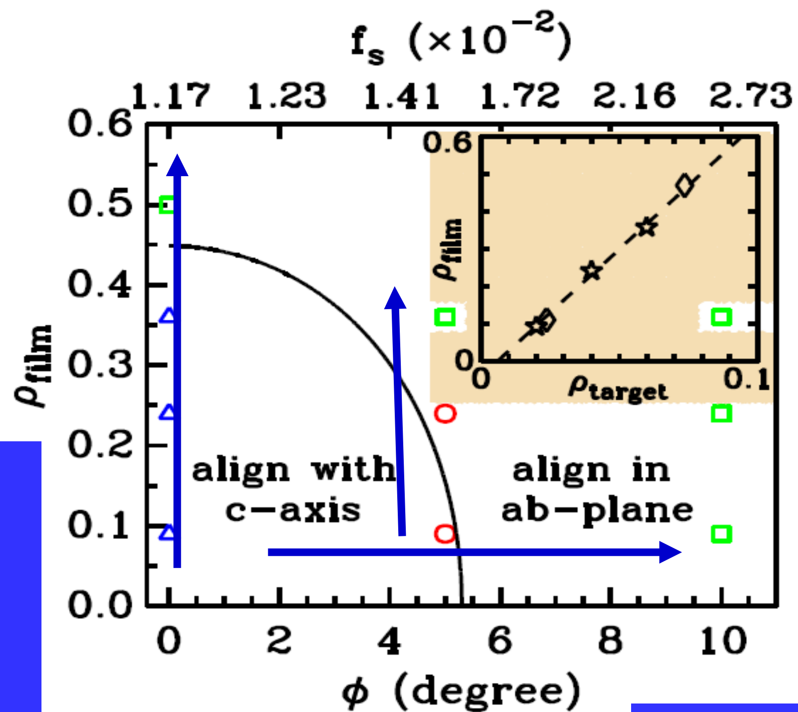
Baca et al., Appl. Phys. Lett. **94**, 102512 (2009); Emergo et al., SUST **23**, 115010 (2010); Wu et al., IEEE Applied Superconductivity 25 (3), 1-5 (2015). Wu et al., SUST 28, 125009(2015)

APC orientation vs. YBCO matrix strain

(controlled by APC concentration and film/substrate lattice mismatch)

Switch of 1D APC orientation

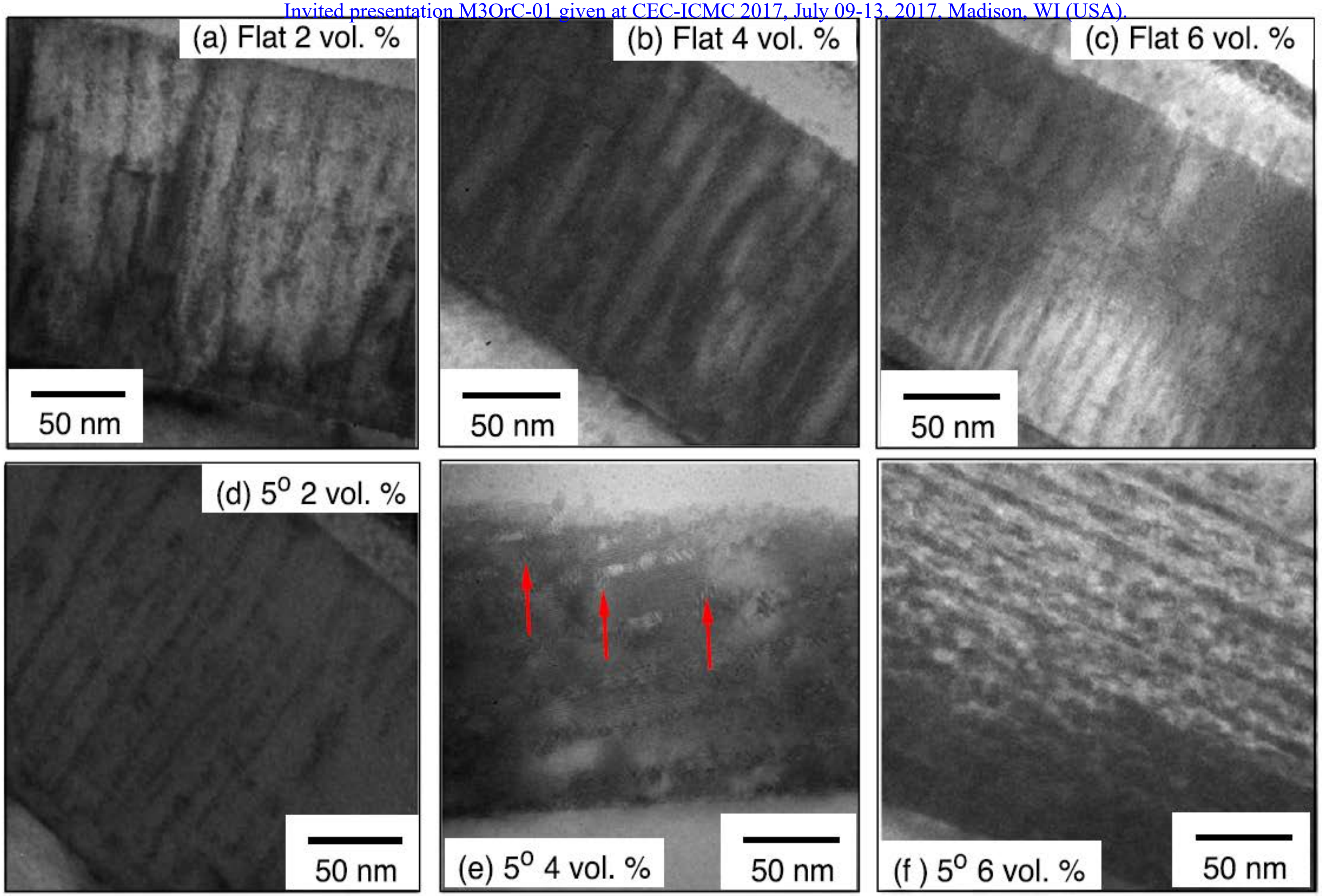
1D APC switch from c-aligned to ab-aligned at high APC concentrations



Switch of 1D APC orientation

1D APC switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

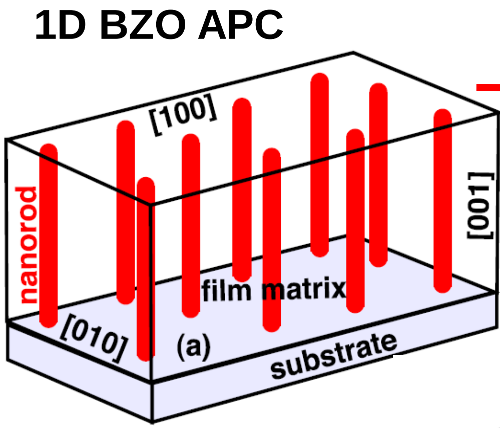
Shi and Wu, *Phil. Magazine* **92**, 2911 (2012); ***92**, 4205* (2012).
F.J. Baca et al., *Adv. Funct. Mat.* **23**, 4628, (2013);
J. Wu et al., *IEEE Trans. Applied Supercond.* **25**, 1-5 (2015);
J. Wu et al., SUST 28, 125009 (2015).
J.Z. Wu, Endless Quests -- Theory, Experiment and Application of Frontiers of Superconductivity, Peking University Press (2016).

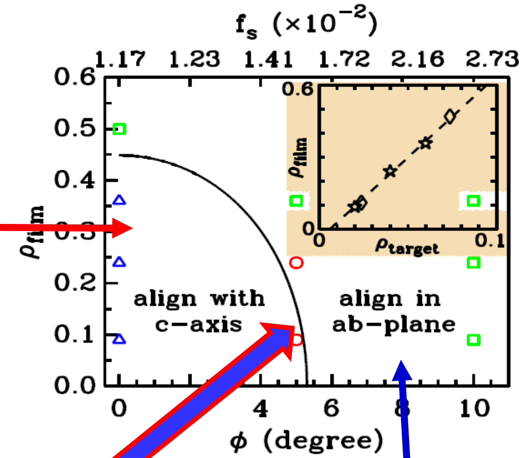


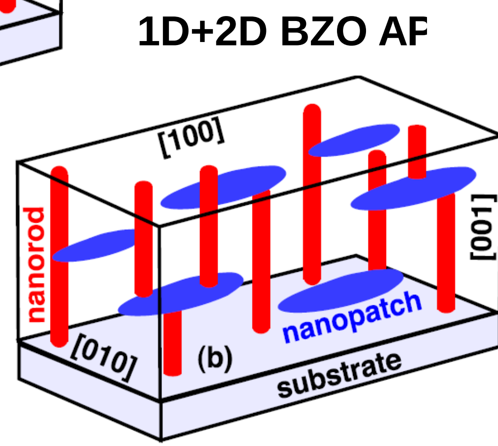
Global strain adds additional tuning parameter on nanorod morphology through interaction with the local strain field

Wu et al., SUST 28, 125009(2015)

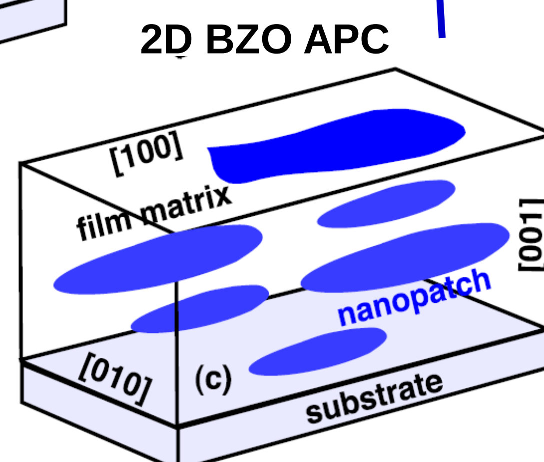
Mixed orientations of 1D+2D APCs

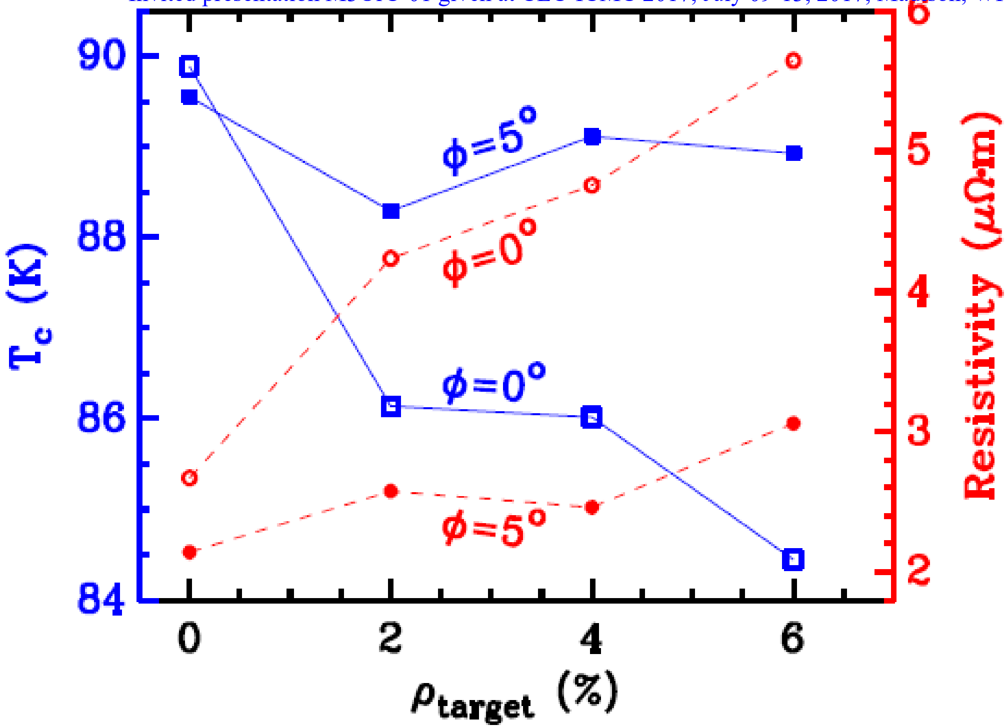






Controlling the interplay between local and global strains

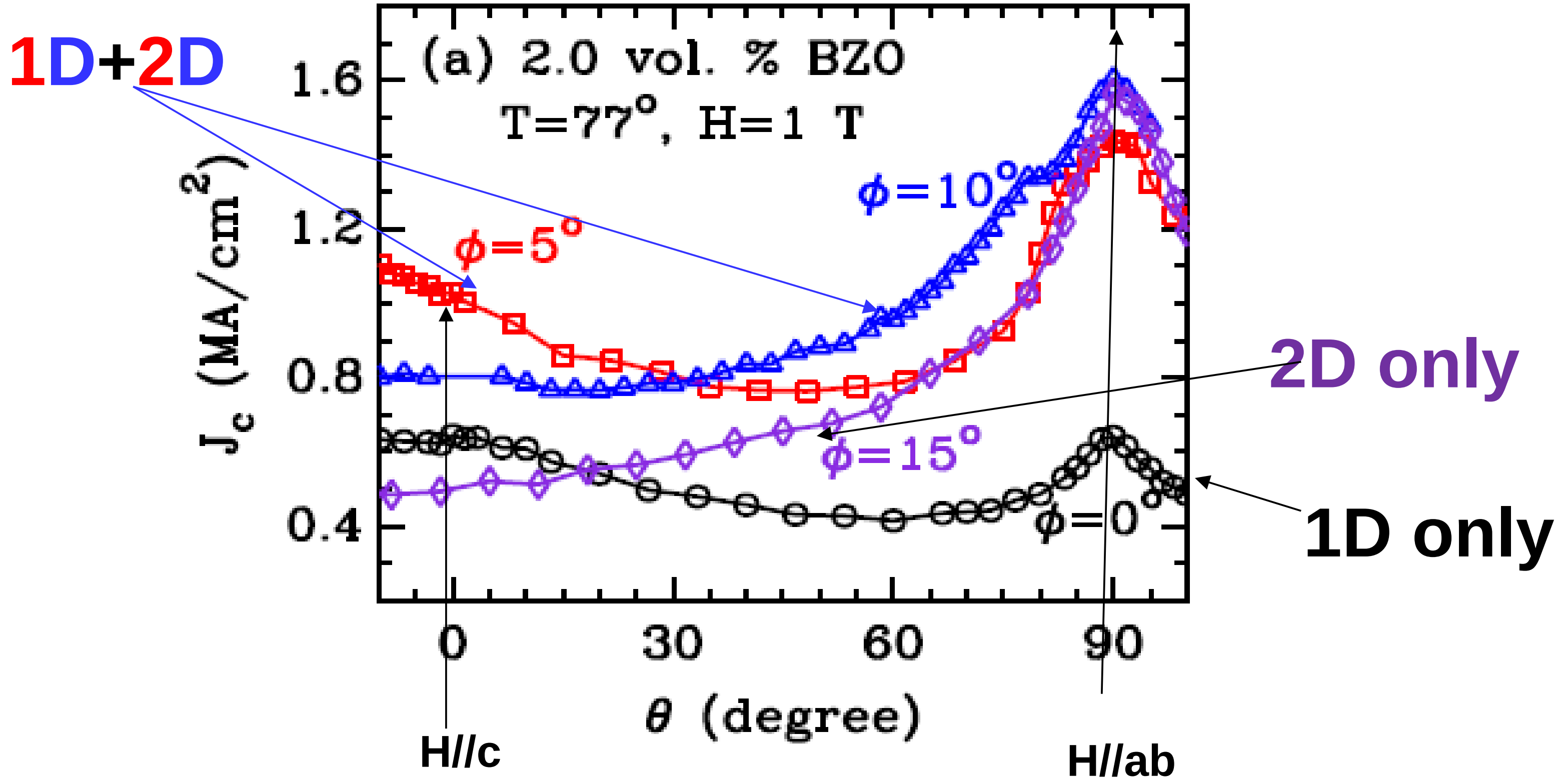




Much smaller reduction in T_c in vicinal samples indicates reduced strain on YBCO lattice—favorable to high Jc

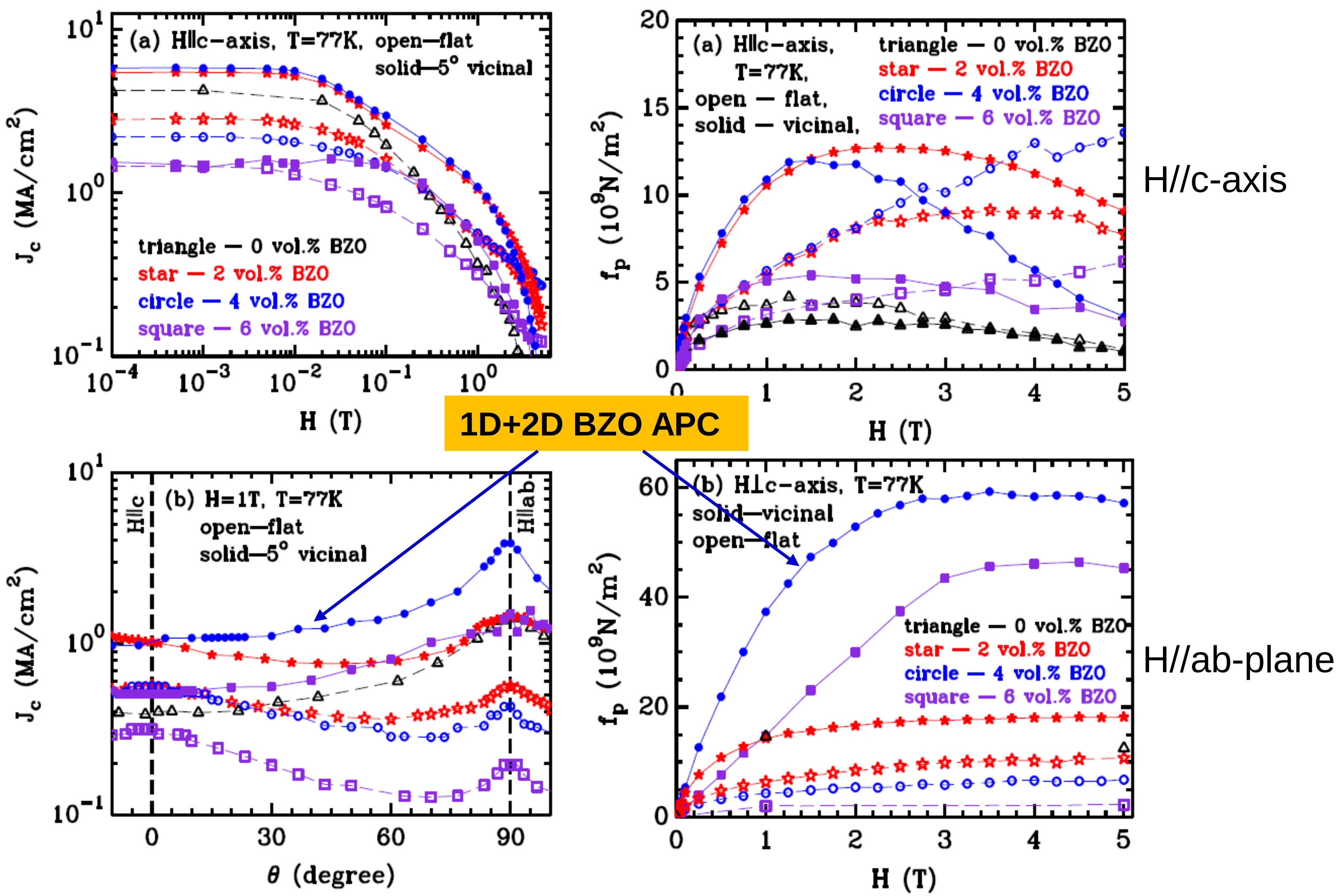
Wu et al., SUST 28, 125009(2015)

Enhancement of J_c in 1D+2D BZO APC doped YBCO films

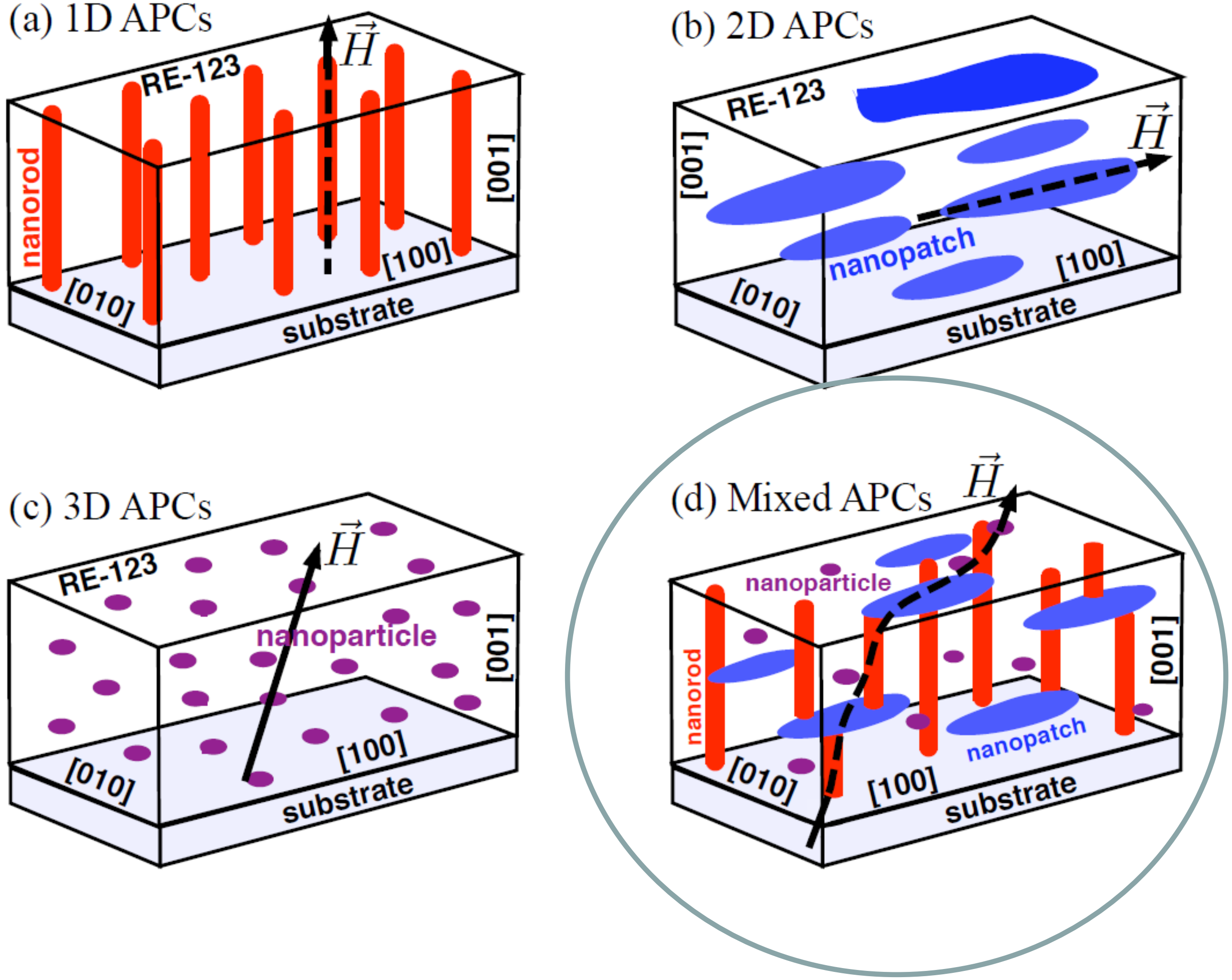


Overall enhanced J_c in all H directions in BZO doped YBCO possibly due to 1) reduced strain on YBCO; 2) mixed orientations of BZO APCs

1D only suffers Jc decrease at high BZO concentrations

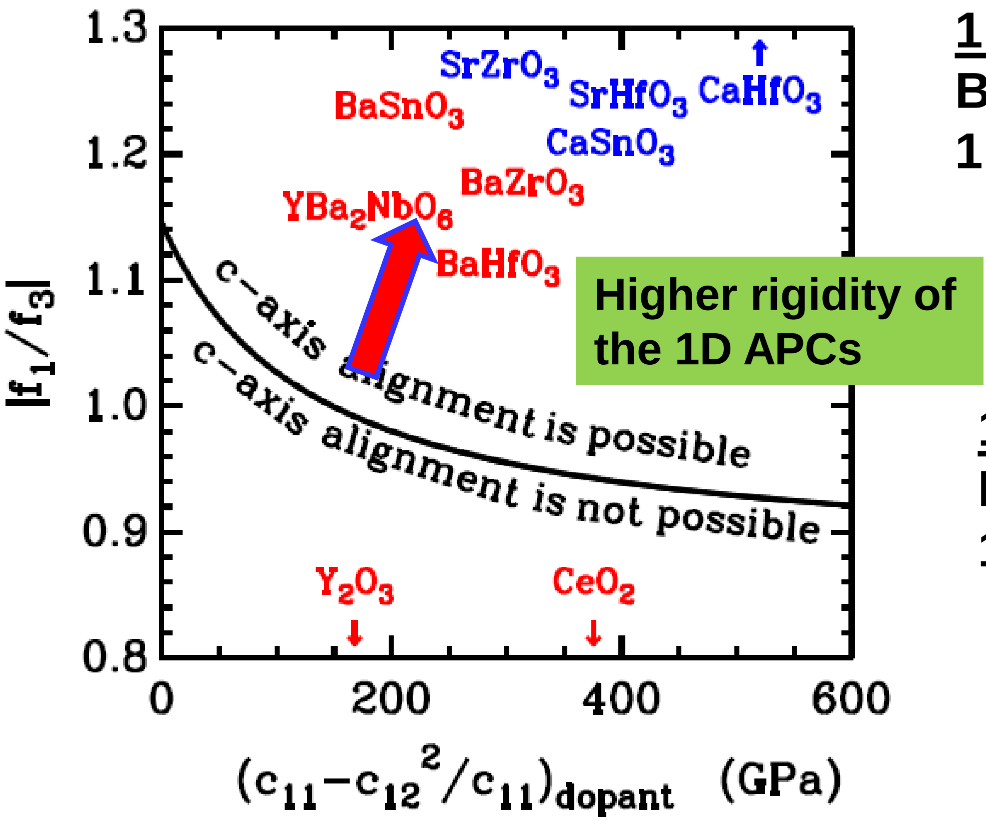


Wu et al., SUST 28, 125009(2015)



1D+2D+3D mixed APCs

Rigidity of 1D APCs –tuning APC morphology using double doping (DD)



Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017) ASAP

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

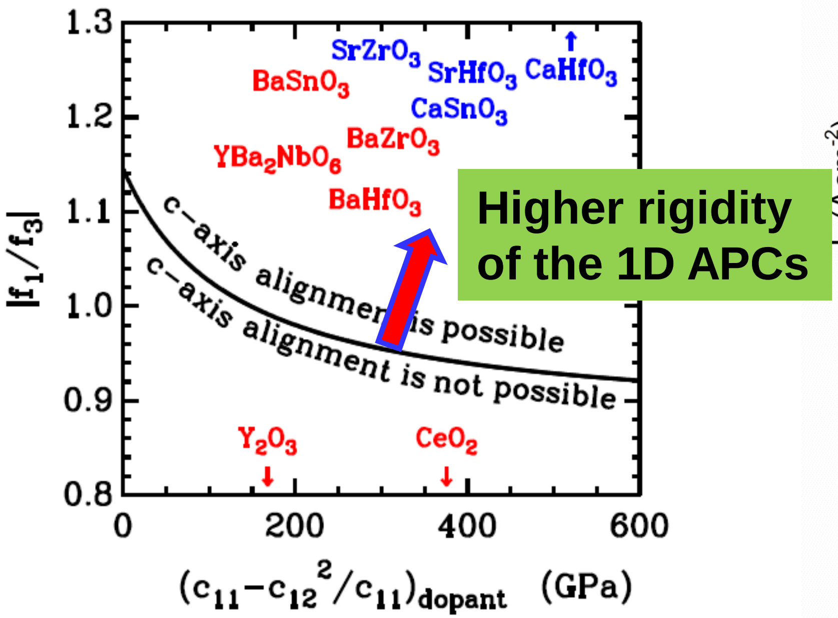
Jha et al, . *IEEE Trans. Appl. Supercond.* **2015,** 25, (3), 1-5.

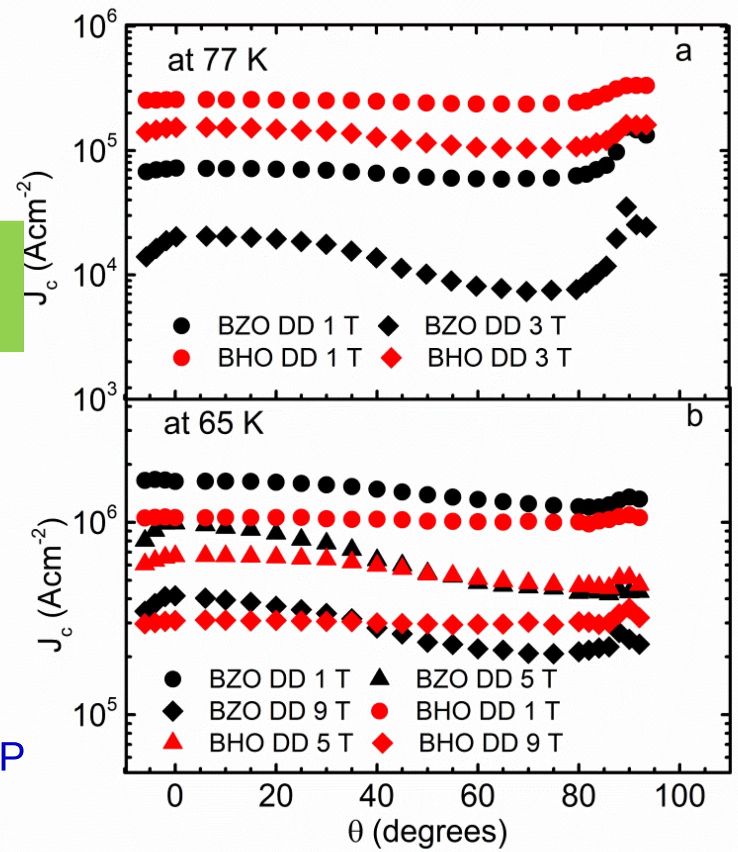
1D APCs with lower rigidity:
BHO (BZO) + Y2O3:
1D + 2D + 3D APCs

B. Maiorov et al., *Nature Mat.* (2009); M. A. P. Sebastian et al., "IEEE Trans on Appl. Supercond., vol. 27, pp. 1-5, 2017.

Rigidity of 1D APCs

BHO DD: 3 vol% Y_2O_3 + 2 vol.% BHO
BZO DD: 3 vol% Y_2O_3 + 2 vol.% BZO



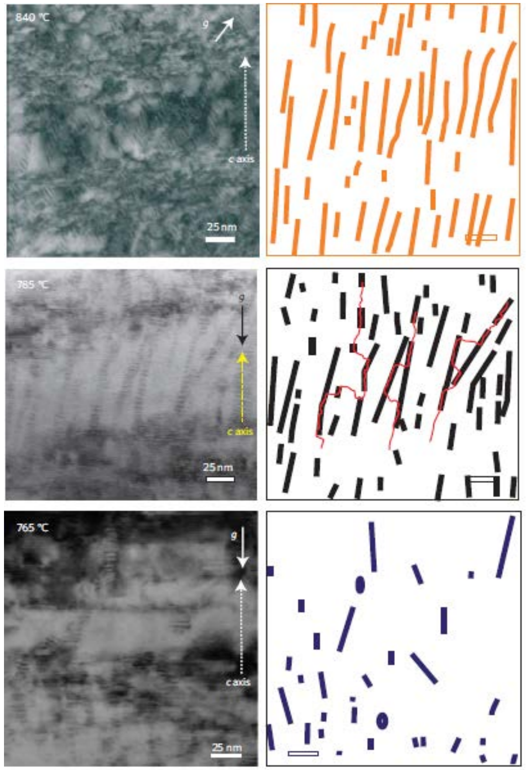


B. Gautam et al., *AIP Advances*, 2017 ASAP

- **1D APCs with higher rigidity tend to remain as c-axis aligned**
- **1D APCs with lower rigidity may be de-aligned in c-axis by additional local strain such as that introduced in secondary APC doping**

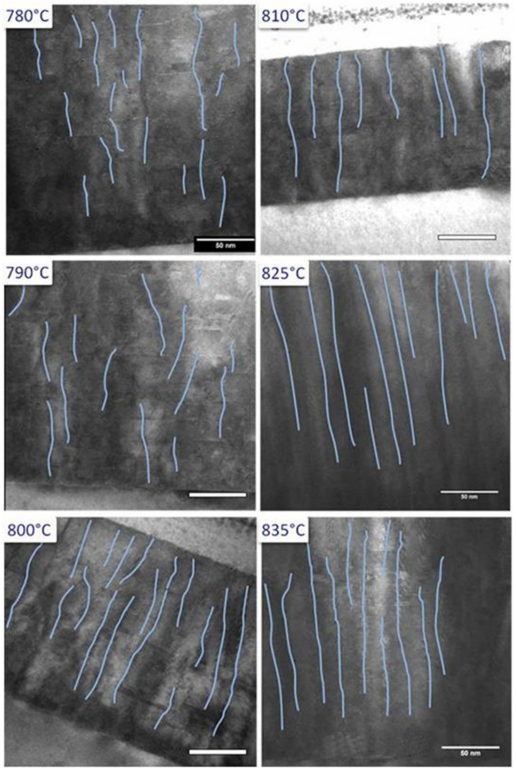
Temperature Effects in Nanorod Formation

2%BZO+5%Y2O3 doping

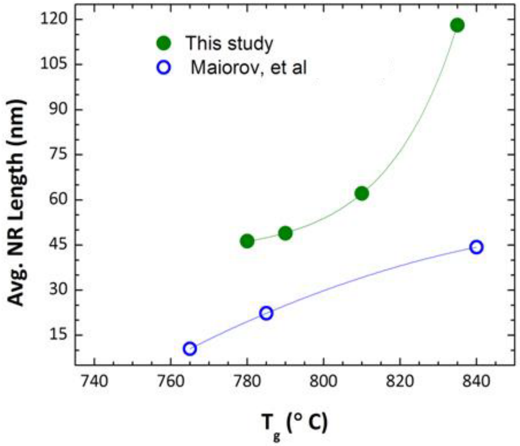


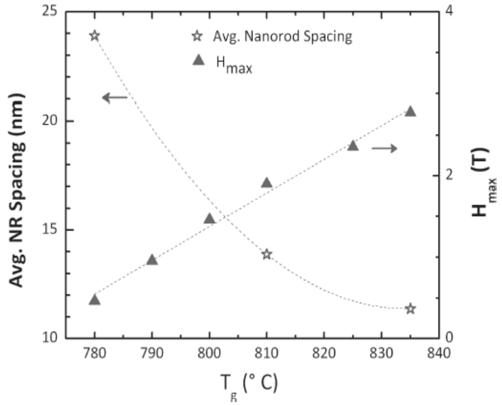
B. Maiorov et al., *Nature Mat.* (2009).

2% BZO doping



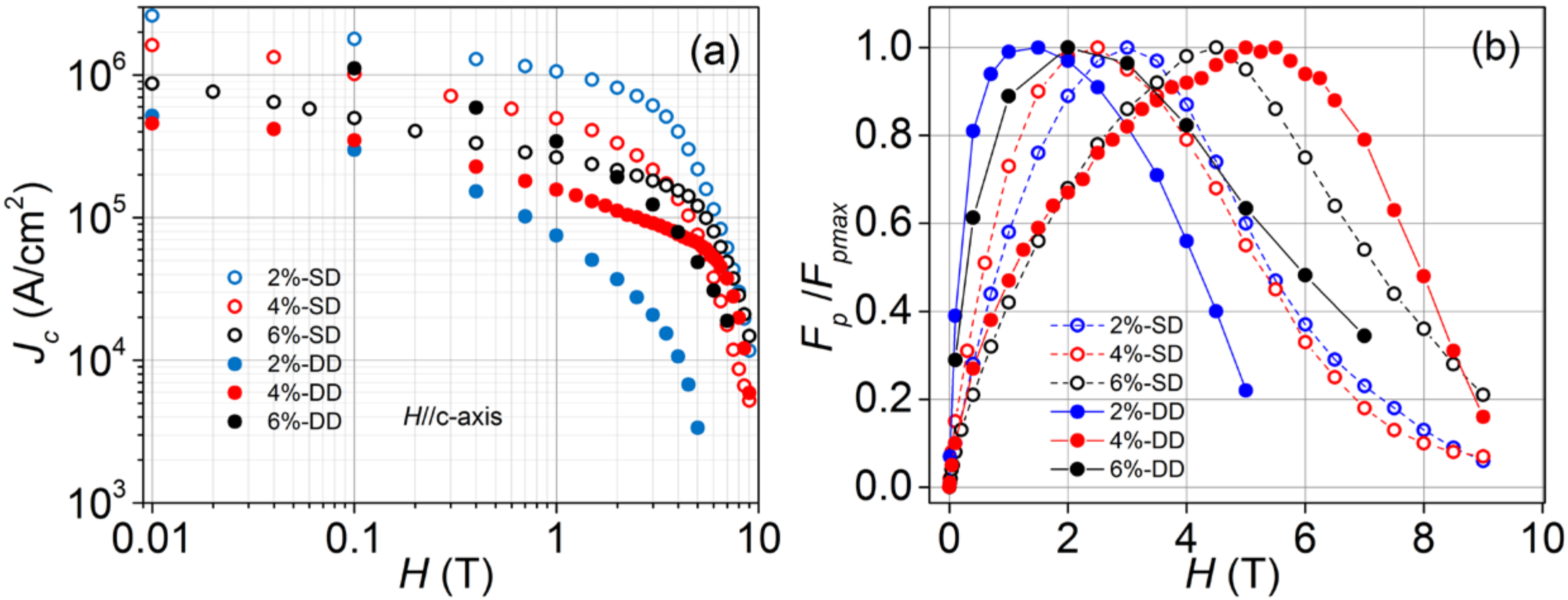
Baca et al., *Adv. Func. Mat., (*2013)





- Y_2O_3 hinders c-axis aligned BZO nanorods formation
- At low Ts, Small-size BZO APCs may not be even visible

Opposite trends in J_c of DD ($BZO+Y_2O_3$) and SD (BZO only) with primary APC concentration

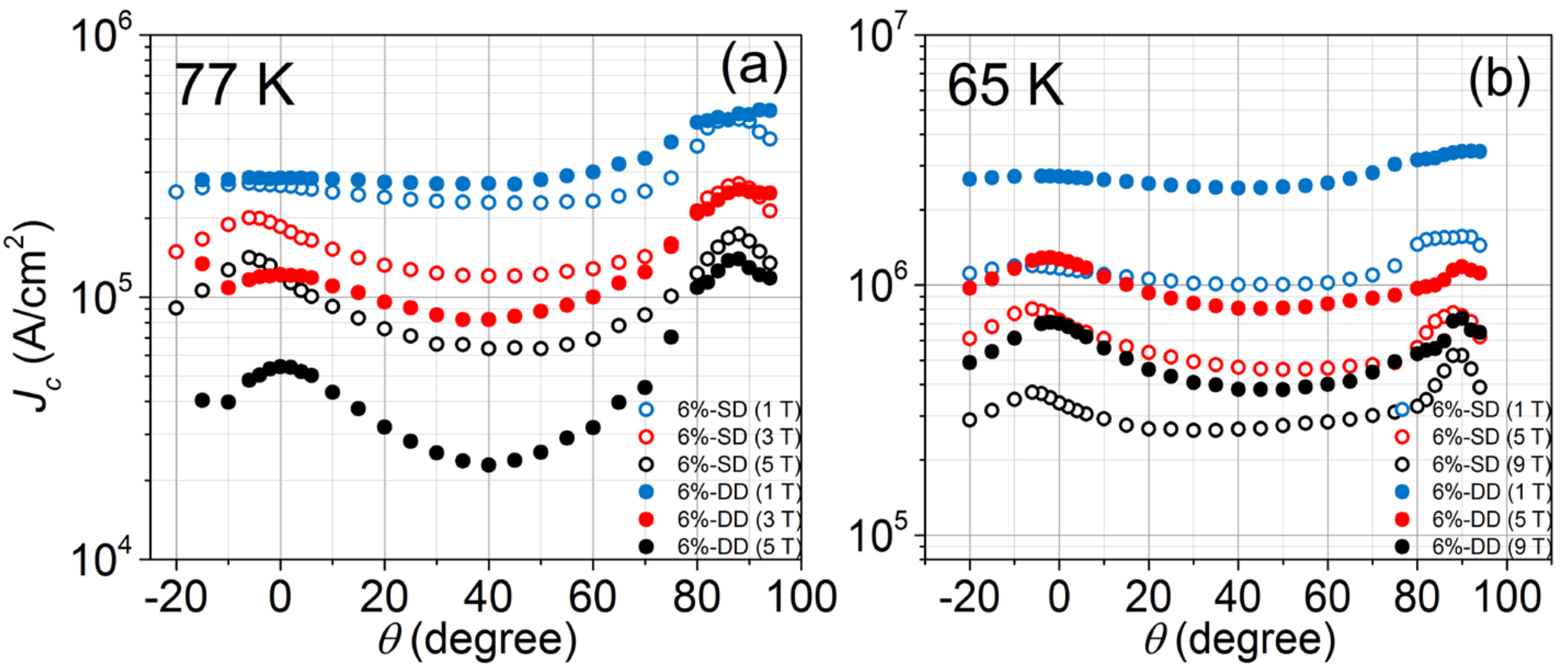


Open: (2, 4, 6 vol.% BZO) SD

Solid: (2, 4, 6 vol.% BZO+ 3 vol.% Y_2O_3) DD

Chen et al., IEEE Transaction on Applied Superconductivity Vol. 27, 2017, Chen et al., CEC-ICMC poster

J_c anisotropy of DD (BZO+Y2O3) and SD (BZO only)



Much reduced Jc anisotropy observed in 6% BZO+Y2O3/YBCO DD samples

Chen et al., IEEE Transaction on Applied Superconductivity Vol. 27, 2017, Chen et al., CEC-ICMC poster

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Summary

- **Understanding the interfacial strains (local and global) provides means to control APC's morphology, orientation and dimension.**
- **Two approaches have been explored to generate mixed APCs:**

➢ **Single-doping APC (BZO, BSO) for 1D+2D APC/YBCO via control of the APC concentration and YBCO in-plane lattice constants (vicinal)**

➢ **Double-doping Y_2O_3 + BZO (or BHO) for 1D+2D+3D APC/YBCO at different concentrations**

- **The mixed APCs provide benefits of strong and isotropic pinning**