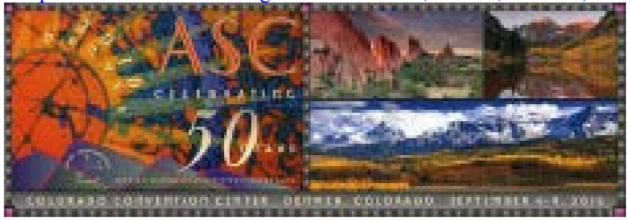
IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Invited presentation 1MOr1B-01 given at ASC 2016; Denver,Colorado,USA, September 4 – 9, 2016.



Development of strong and isotropic $BaZrO_3$ artificial pinning centers in YBCO films

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U.S. Air Force Research Laboratory, USA

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September 5, 2016, Denver, Colorado

KU THE UNIVERSITY OF KANSAS

Outline of this talk

Introduction

- Effect of Interfacial strain on the self-assembly of artificial pinning centers (APCs)
- Quantitative explain, predict and control the pinning landscape

Development of strong 3D BZO APCs in YBCO

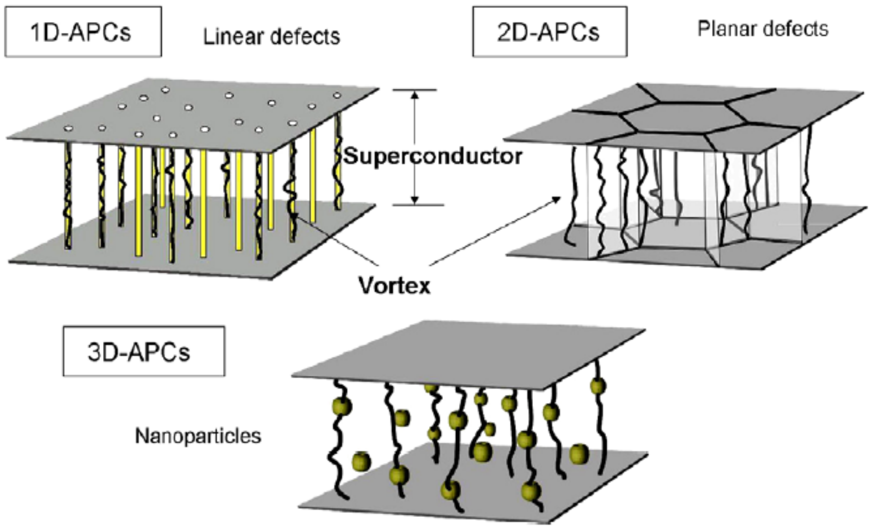
- Vicinal + BZO variable concentration
- Y_2O_3 +BZO variable concentration
- Low T growth BZO/YBCO + high-T post-anneal

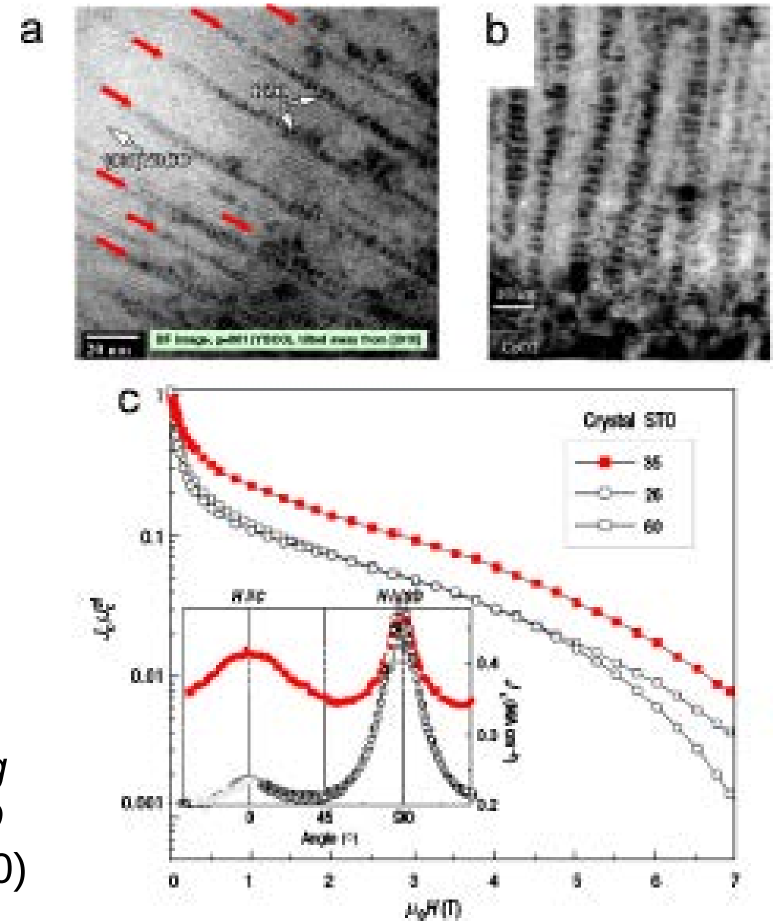
Summery

Goal: strong and isotropic pinning

Artificial Pinning Centers (APCs) landscape

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

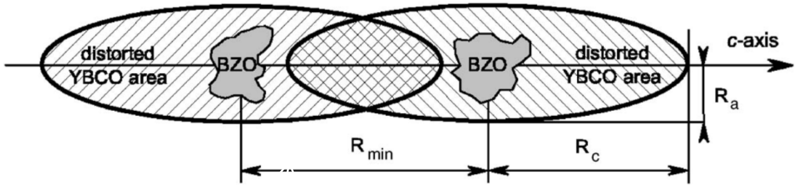




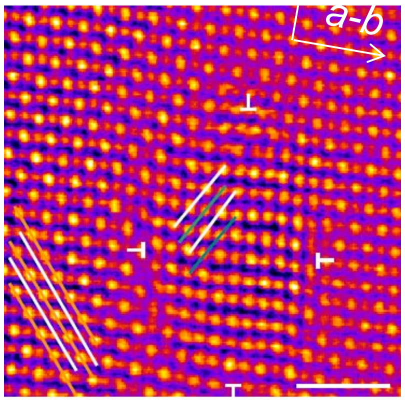
Matsumoto and Mele, topic review on *Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors*, Supercond. Sci. Technol. 23 (2010) 014001;

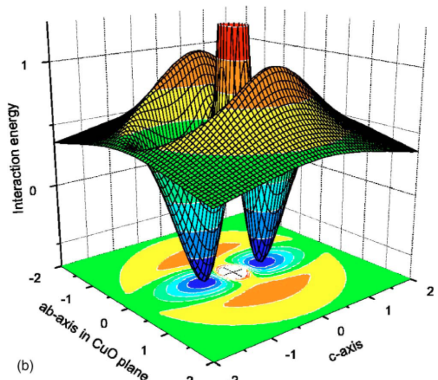
Obradors et al, topic review on Growth, nanostructure and vortex pinning in superconducting YBa2Cu3O7 thin films based on trifluoroacetate solutions, Supercond. Sci. Technol. 25 (2012) 123001

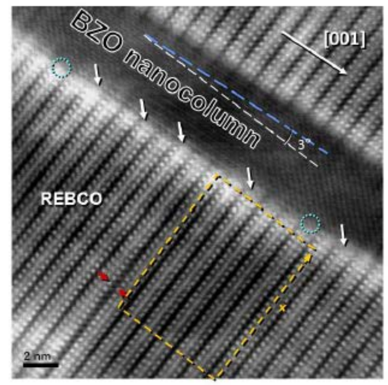
Strain-mediated self-assembly of APCs in epitaxial YBCO matrix: Interfacial Strain Effect

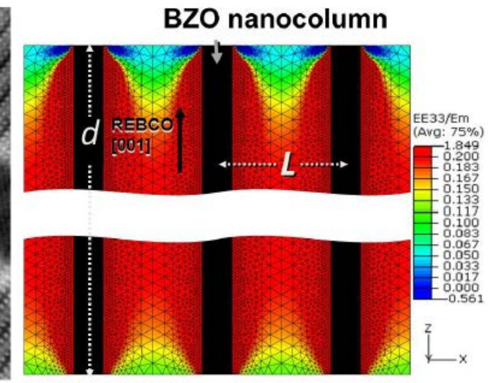


Oxygen deficient column around the BZO/YBCO strained interface-semi-coherent









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**

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?
- **Strong and isotropic:** how to obtain 3D pinning landscape?

Approaches:

Modeling + fabrication + characterization

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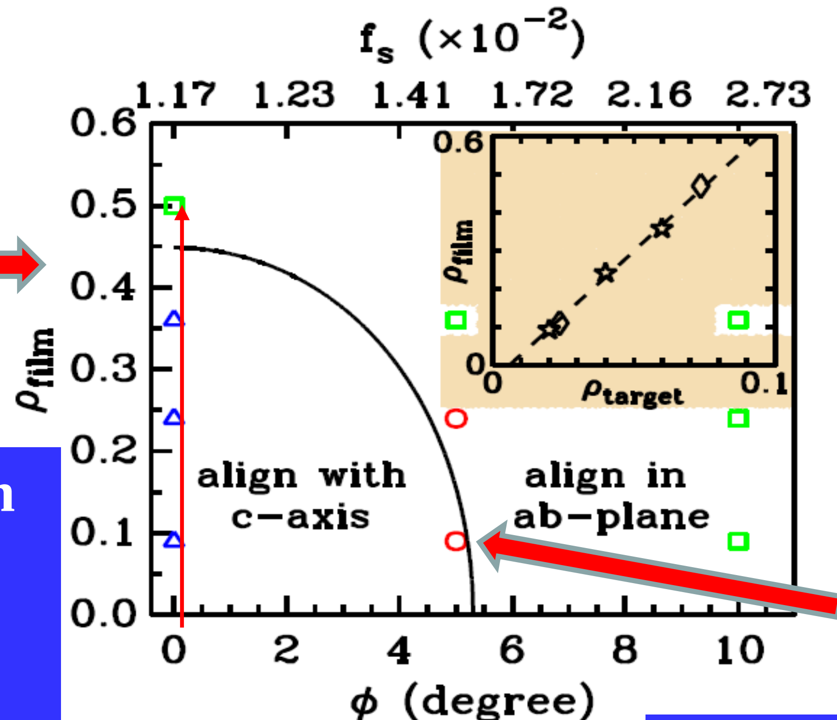
Correlating Effect of doping concentration and film/substrate strains on nanorod morphology

Switch of nanorod orientation

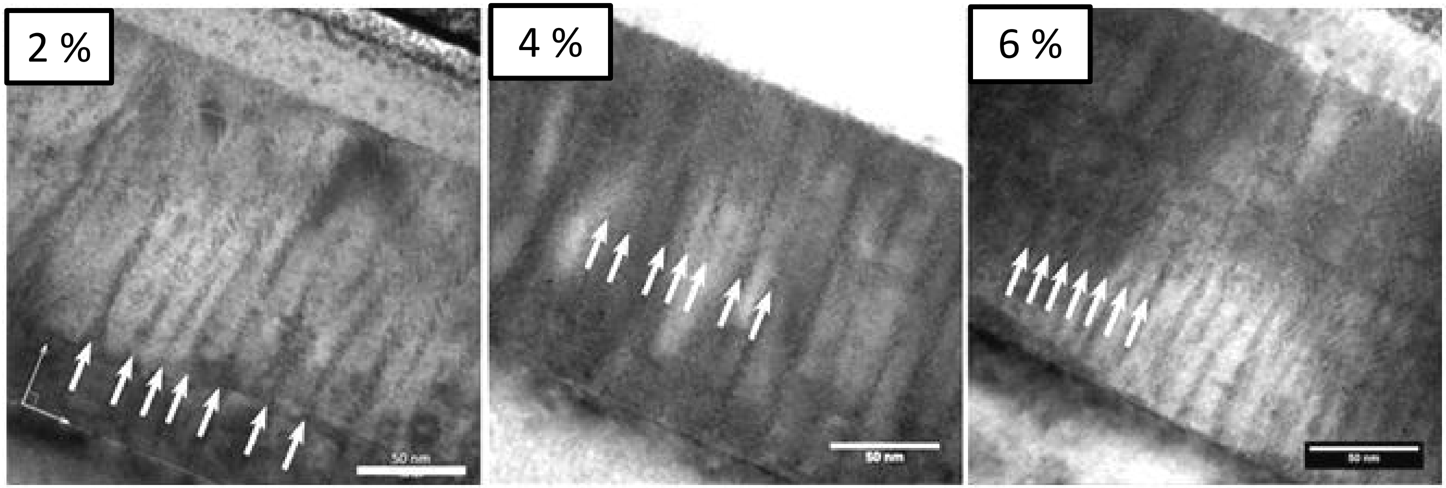


Switch of nanorod orientation

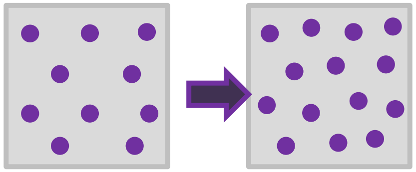
BZO nanorods switch from c-aligned to ab-aligned at 45% BZO vol. portion

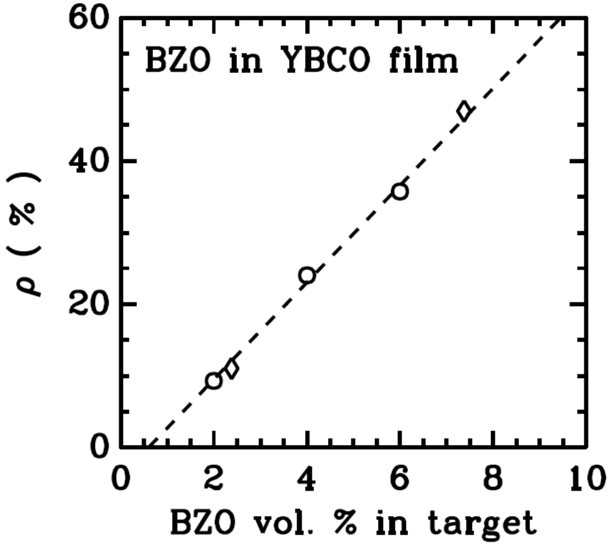
BZO nanorods switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

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



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



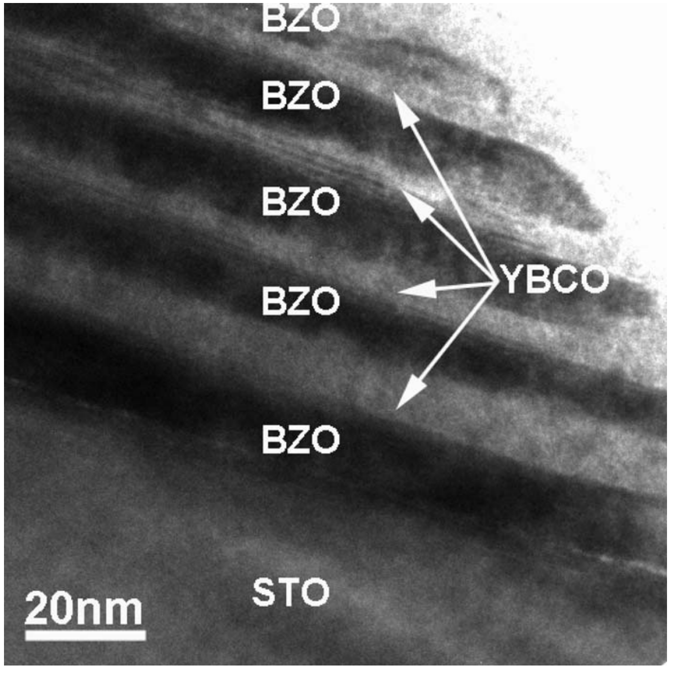


Overlap of the strained matrix around BZO nanorods occurs at around ρ~45% volume portion

- 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).

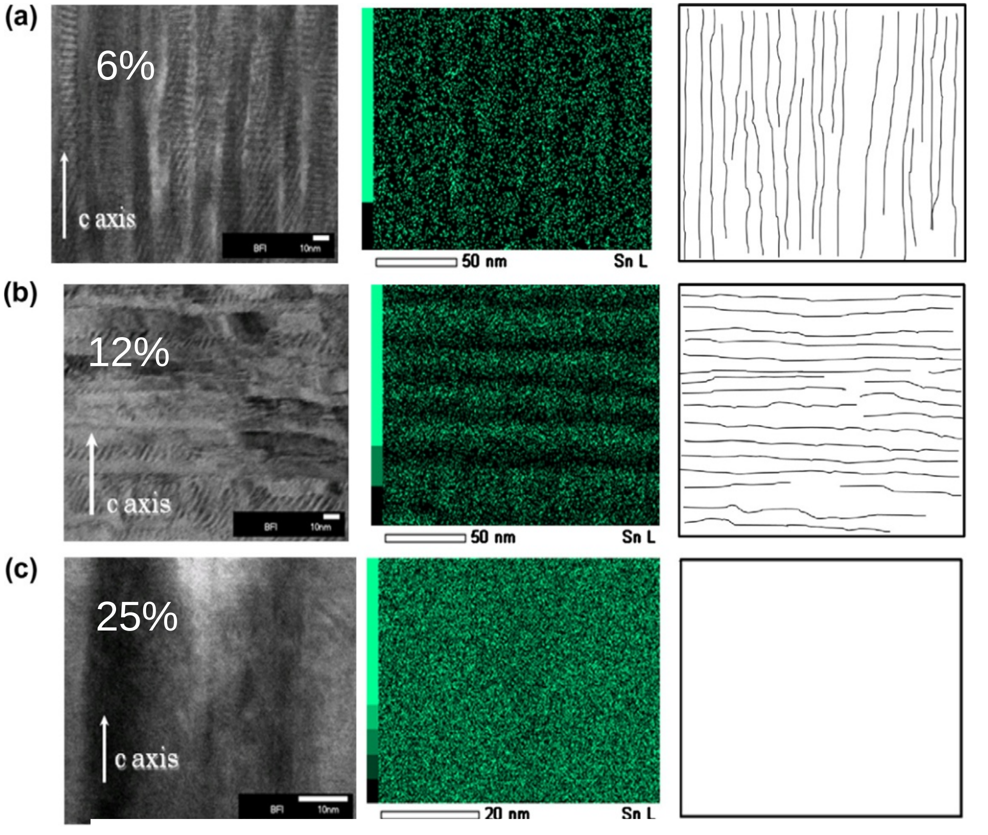
Alignment switch at higher doping levels (nonvicinal)

YBCO:BZO=50%:50%



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

BSO doping (Vol%) in YBCO

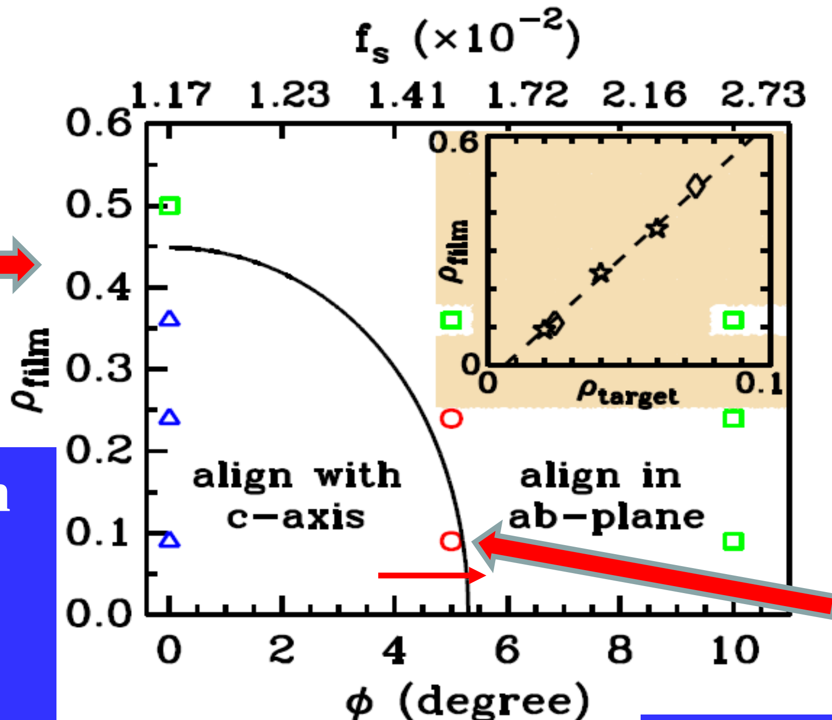


S. Nagao et al, Physica C 470, 1304 (2010)

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

Correlating Effect of doping concentration and film/substrate strains on nanorod morphology

Switch of nanorod orientation



Switch of nanorod orientation

BZO nanorods switch from c-aligned to ab-aligned at 45% BZO vol. portion

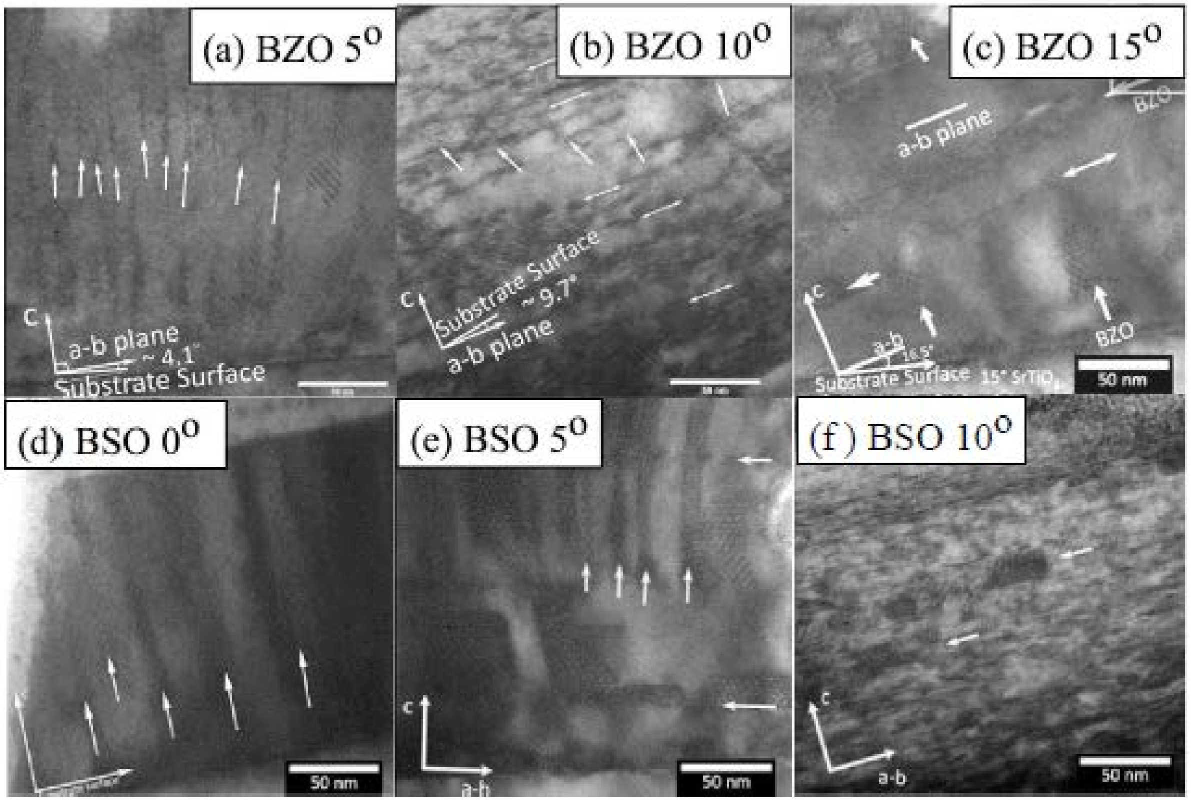
BZO nanorods switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

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

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

2 vol% BZO doping

4.5 vol% BSO doping



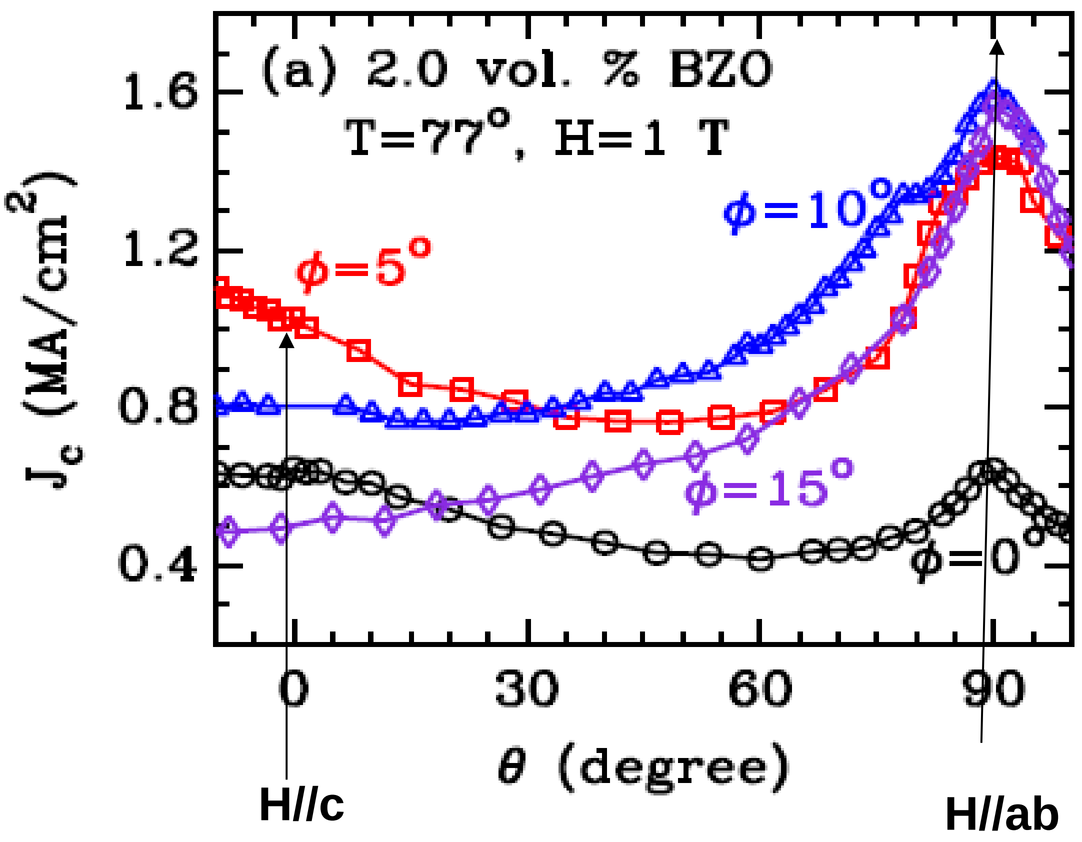
Tensile strain in c-axis

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)

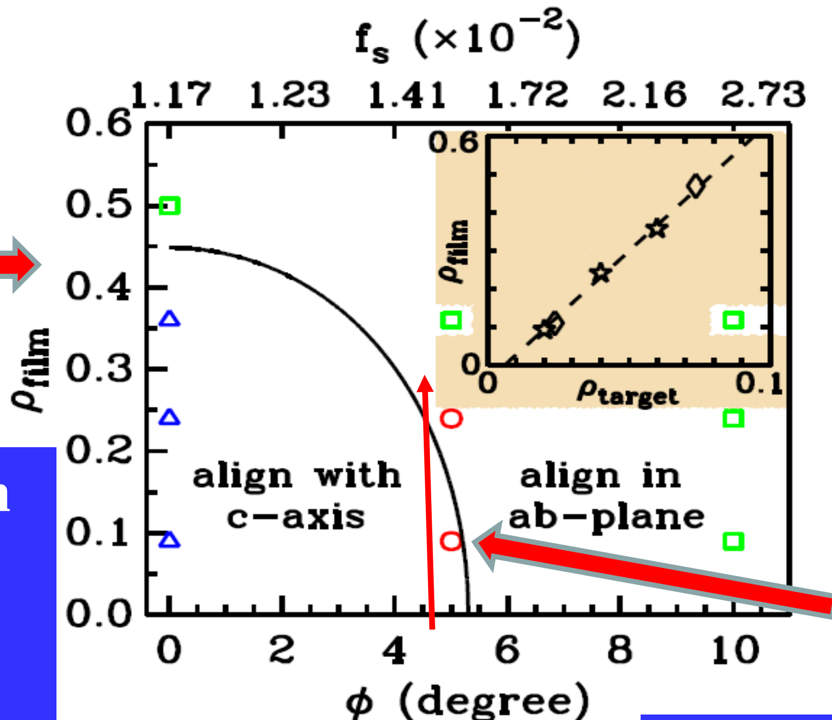
Enhancement of J_c in 3D BZO APC doped YBCO films



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

Correlating Effect of doping concentration and film/substrate strains on nanorod morphology

Switch of nanorod orientation



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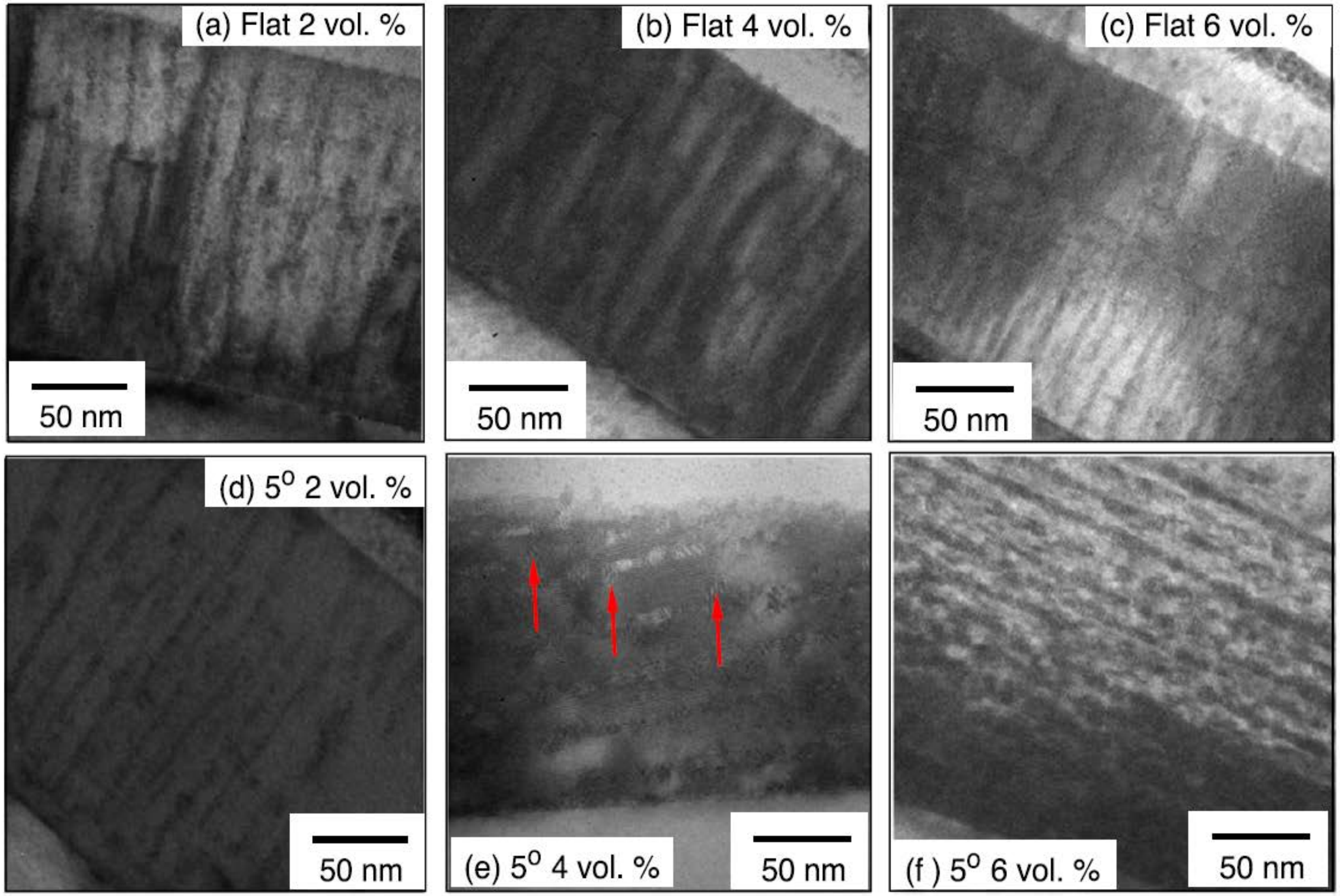
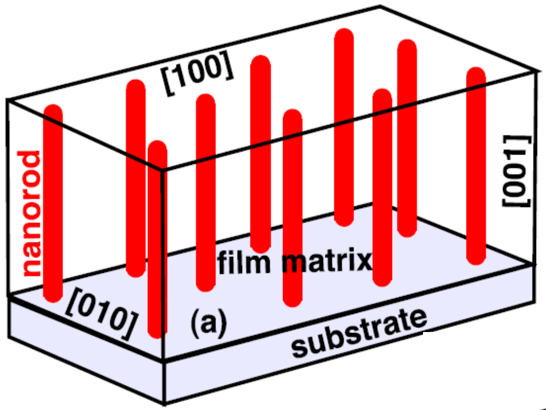


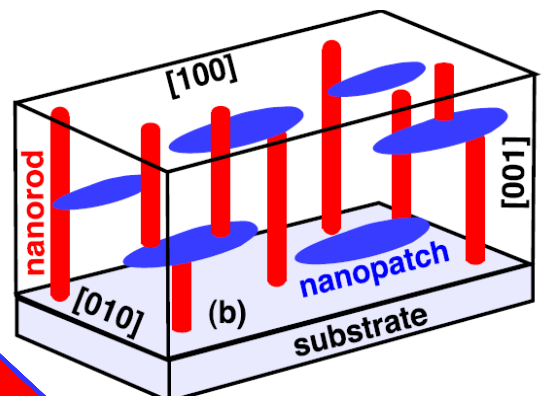
Global strain adds additional tuning parameter on nanorod morphology through interaction with the local strain field

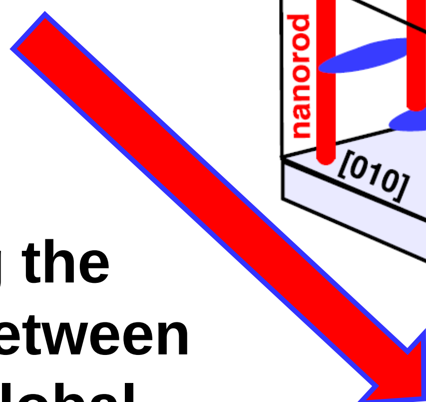
Wu et al, SUST 28, 125009(2015)

1D BZO APC

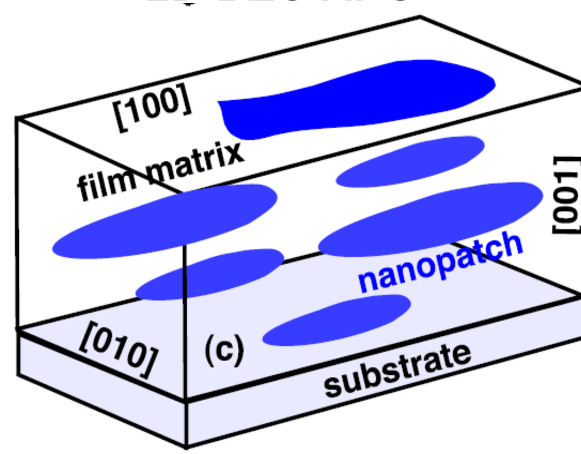


1D+2D BZO APC

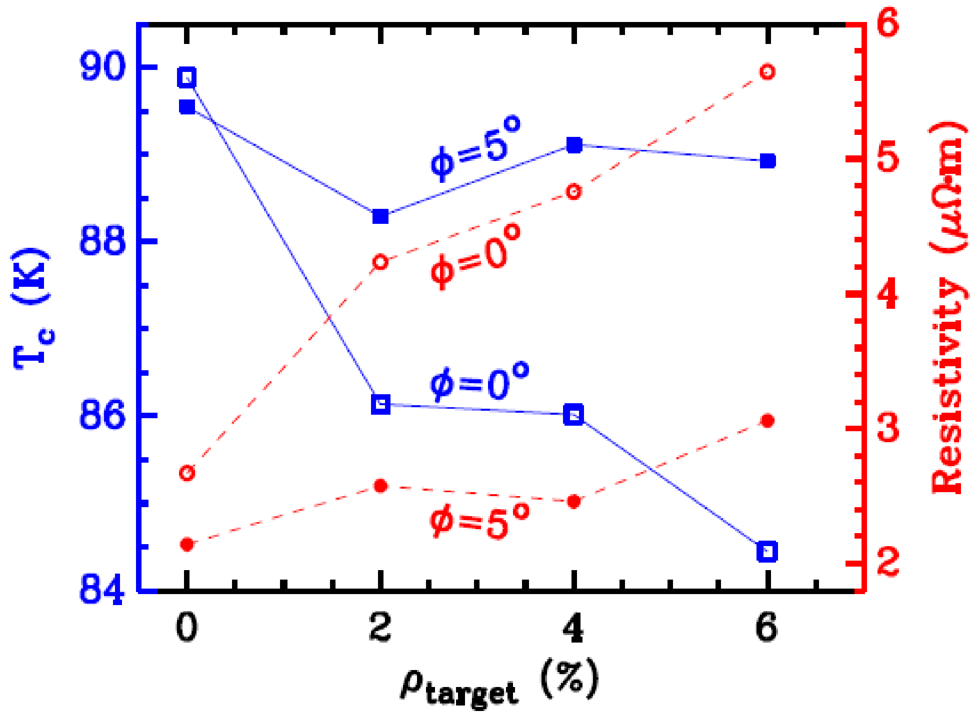




2D BZO APC

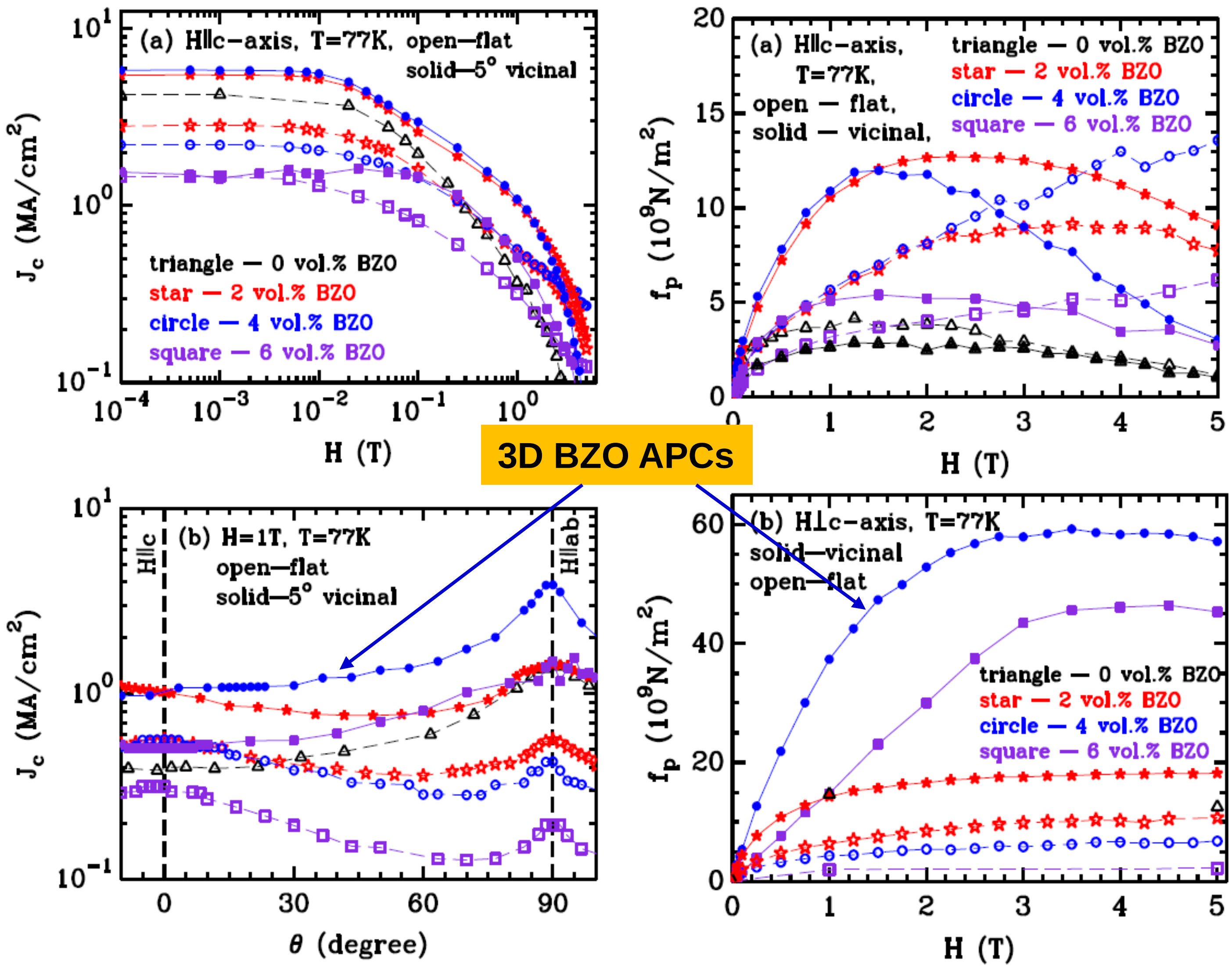


Controlling the interplay between local and global strains



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

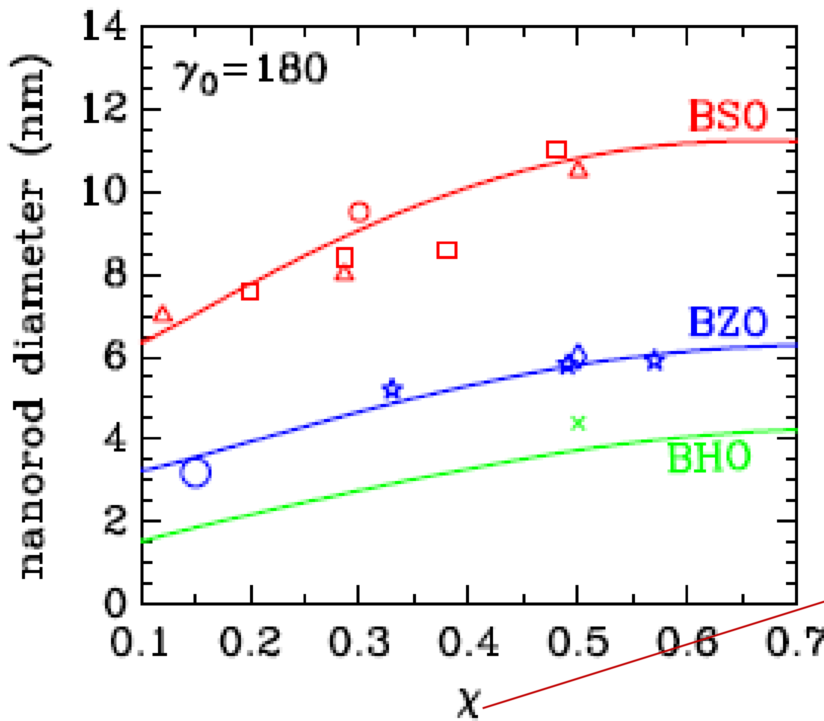
Wu et al, SUST 28, 125009(2015)

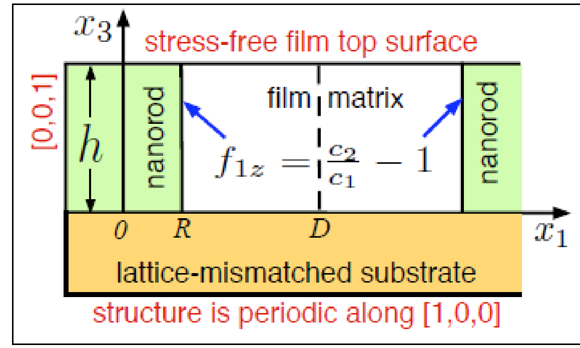


Wu et al, SUST 28, 125009(2015)

Effect of APC concentration and growth temperature on the 1D APC diameter

2MOr1C-06
Tomorrow
10:15am





χ=2R/(D+2R)

χ∝ρ (doping concentration)

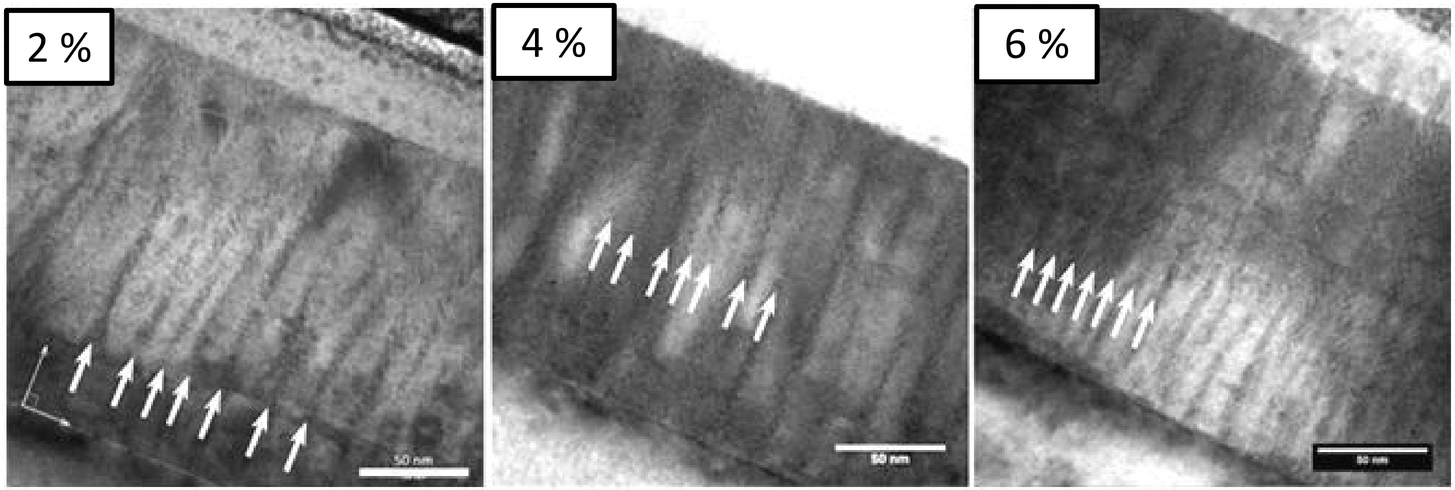
χ is the ratio of nanorod diameter to center-to-center distance.

triangle: Varanasi et al, (2008); square: Mele et al, (2009); circle: Baca, (2009). large circle: Goal et al, (2005); star: Wu et al, (2014); diamond: Selvamanickam et al, (2015). cross: Tobita et al, (2012).

Wu, et al, Supercond. Sci. Technol, **27**, 044010 (2014); Shi and Wu, JAP **118**, 164301 (2015).

Diameter of Nanorods remains a constant

Increased nanorod density with increased dopant concentration



BZO vol. concentration	*2%*	*4%*	*6%*
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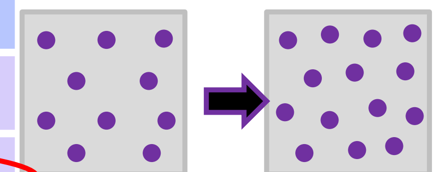
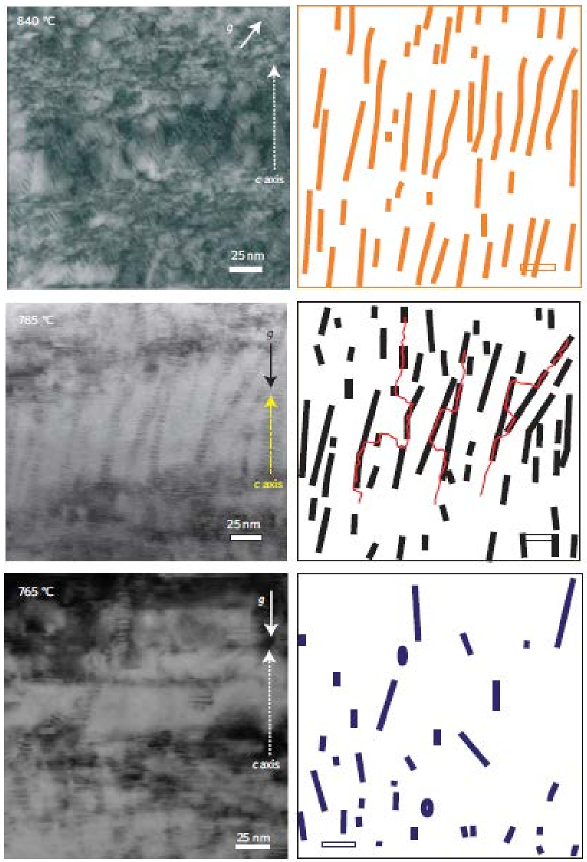


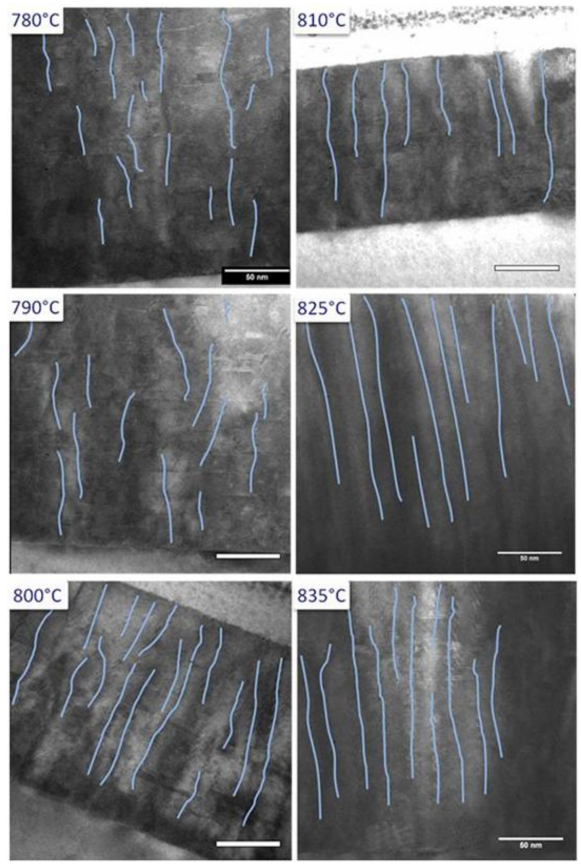
The diameter of the nanorod is determined by the semi-coherent "ultrathin" interface between the dopant and matrix and is almost a constant at low to moderate doping level

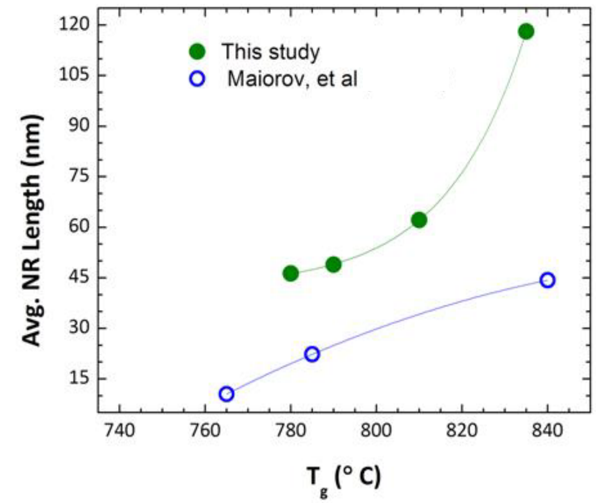
Temperature Effects in Nanorod Formation

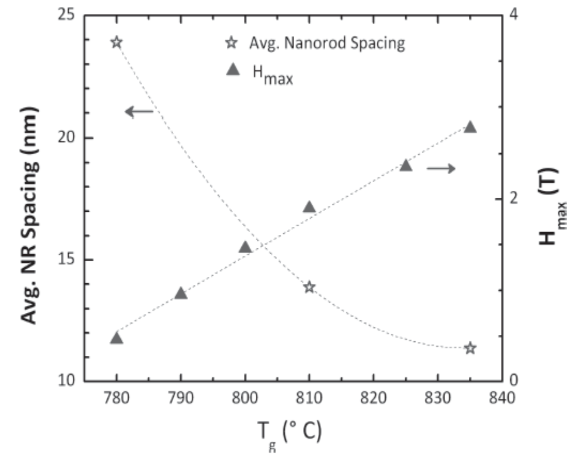
2%BZO+5%Y2O3 doping



2% BZO doping







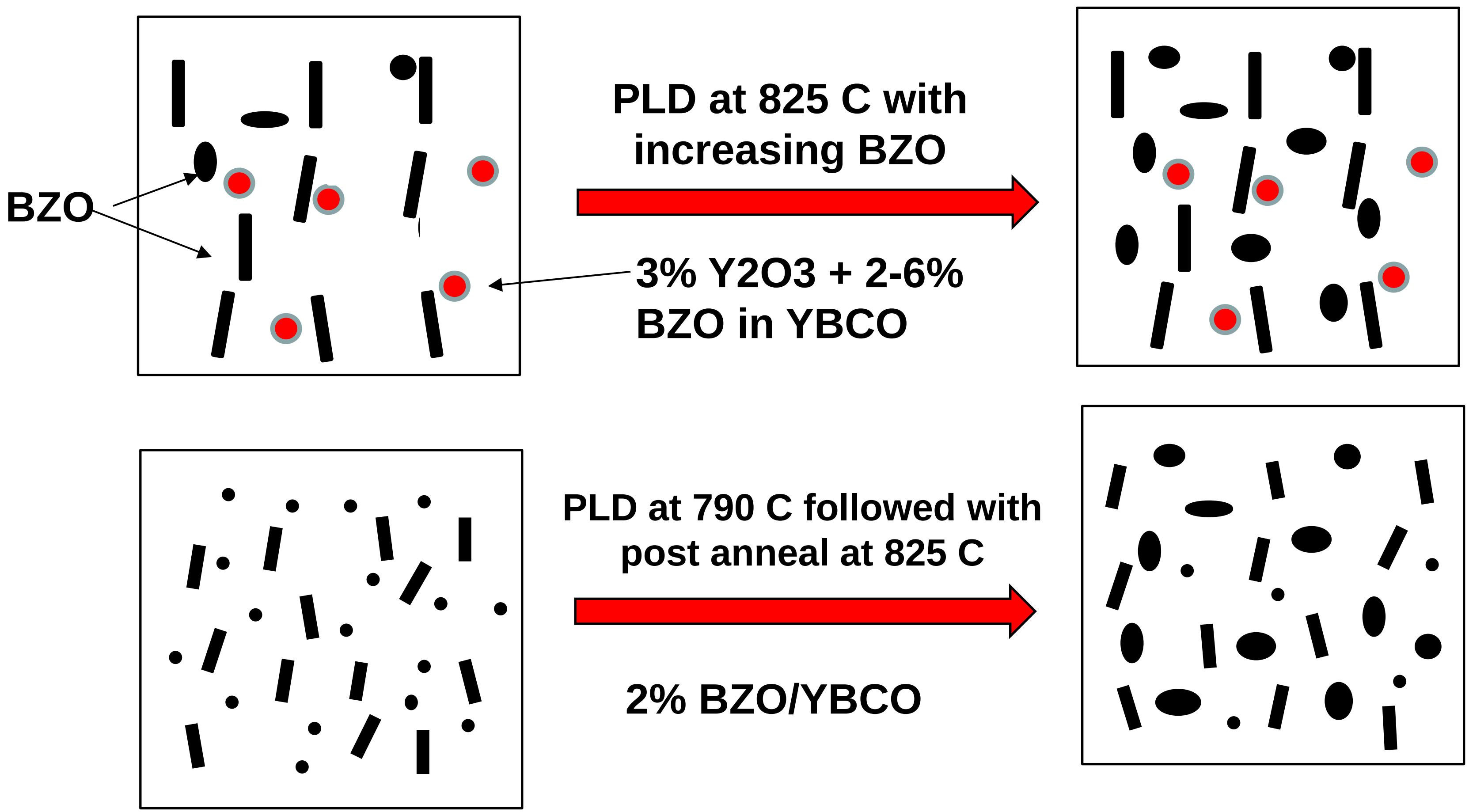
B. Maiorov, et al. *Nature Mat.* (2009).

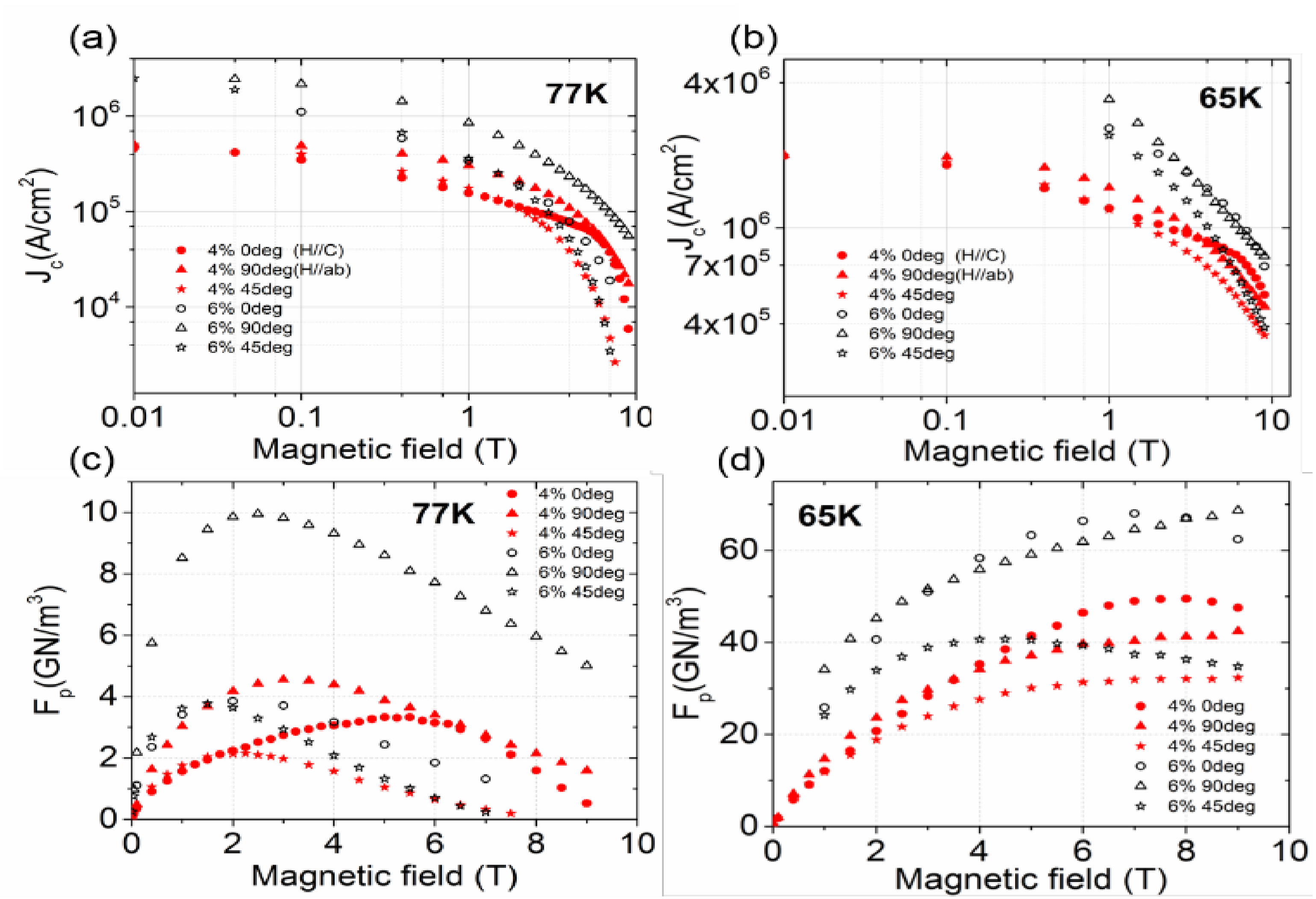
Baca et al, *Adv. Func. Mat., (*2013)

- **Y_2O_3 hinders c-axis aligned BZO nanorods formation**
- **Large amount of small-size BZO APCs may not be even visible**

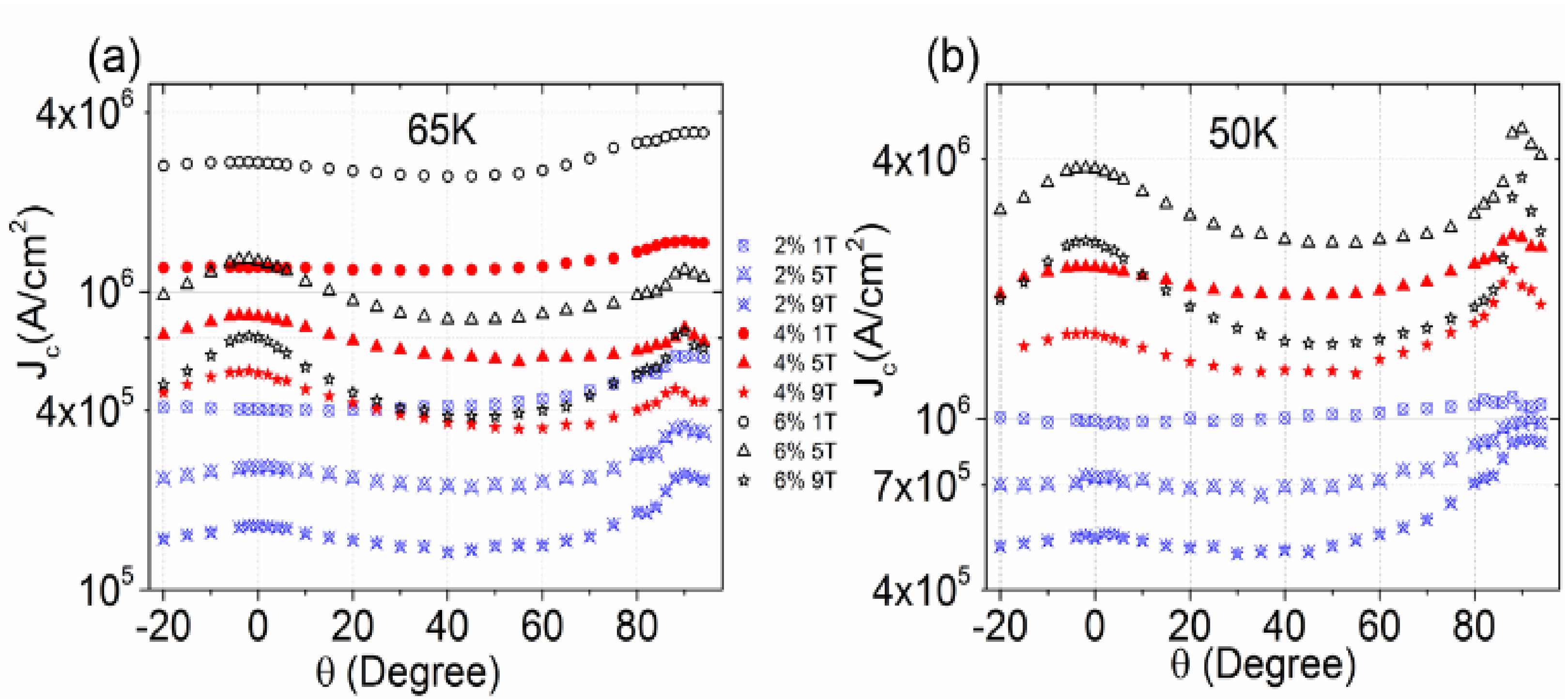
Two approaches to develop 3D BZO APCs:

- BZO+Y_2O_3/YBCO at high BZO concentration
- Low T growth BZO/YBCO + high-T post-anneal



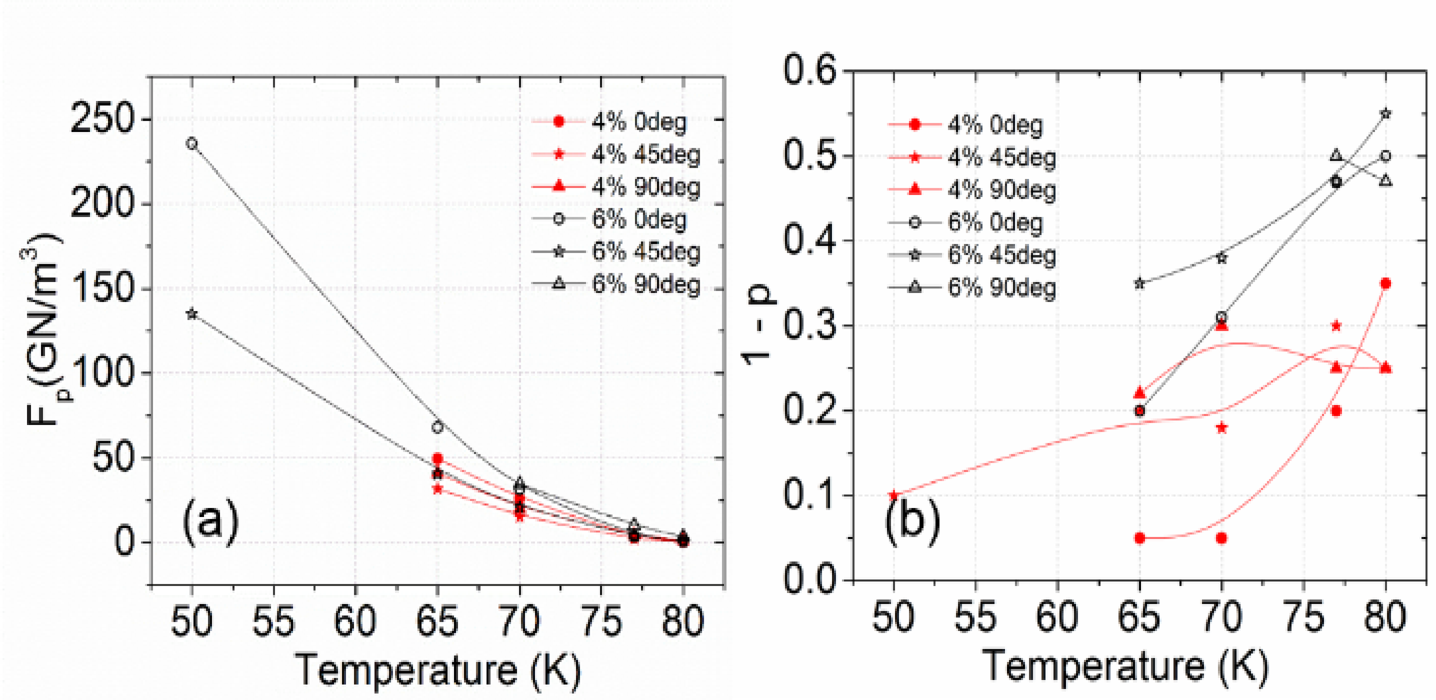


Significantly enhanced overall Jc and Fp in 6% BZO+Y2O3/YBCO samples



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

Chen et al, submitted



Fit the F_p (H) using the model by Dew-Hughes and Kramer, 1-P=*α*,

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

Chen et al, submitted

Besides overall high Fp in 6% BZO+Y2O3, the low 1-P value at 45 deg orientation indicates 3D BZO APCs can be strong pins at low temperatures

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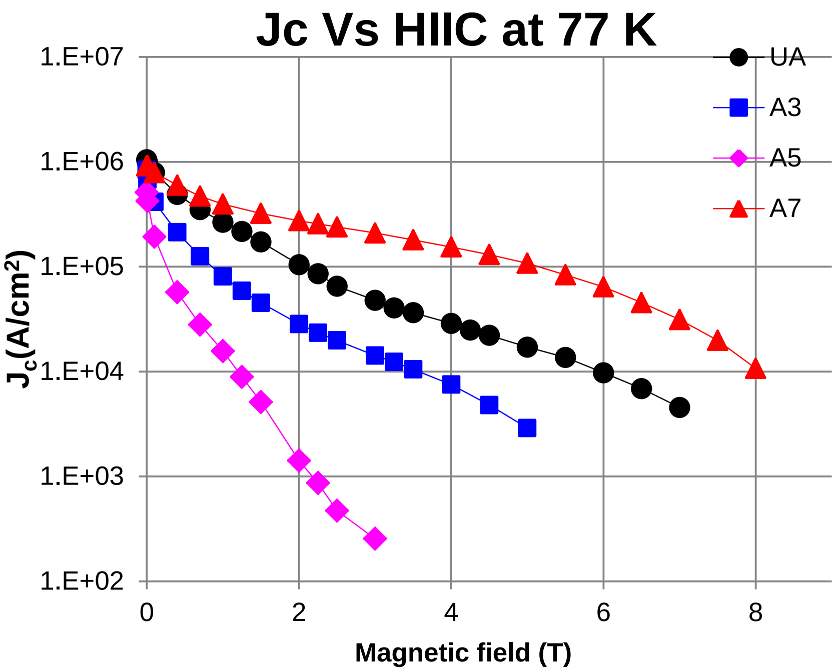
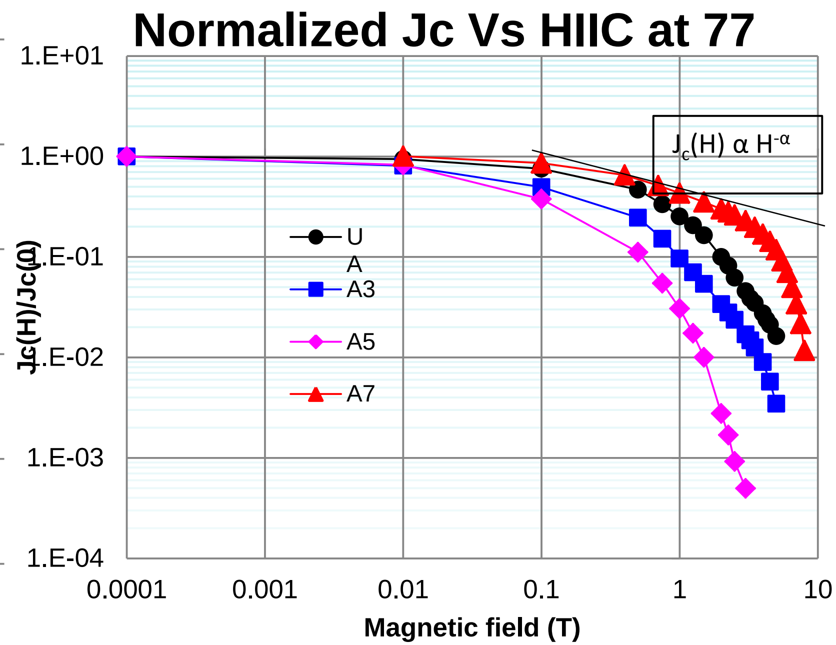
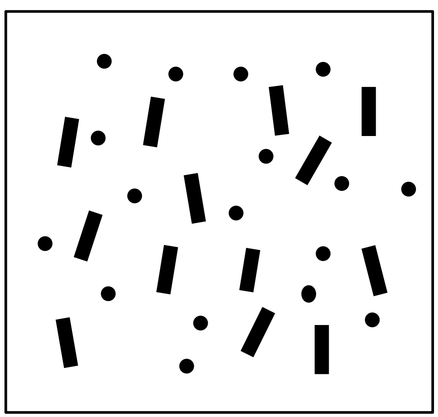
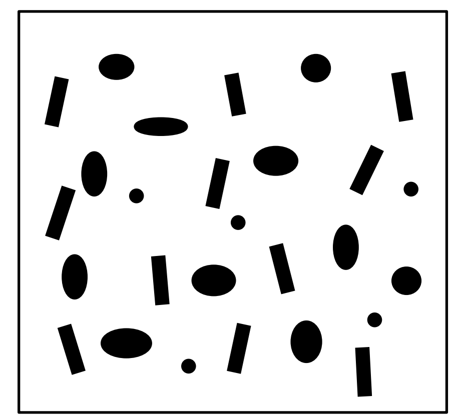






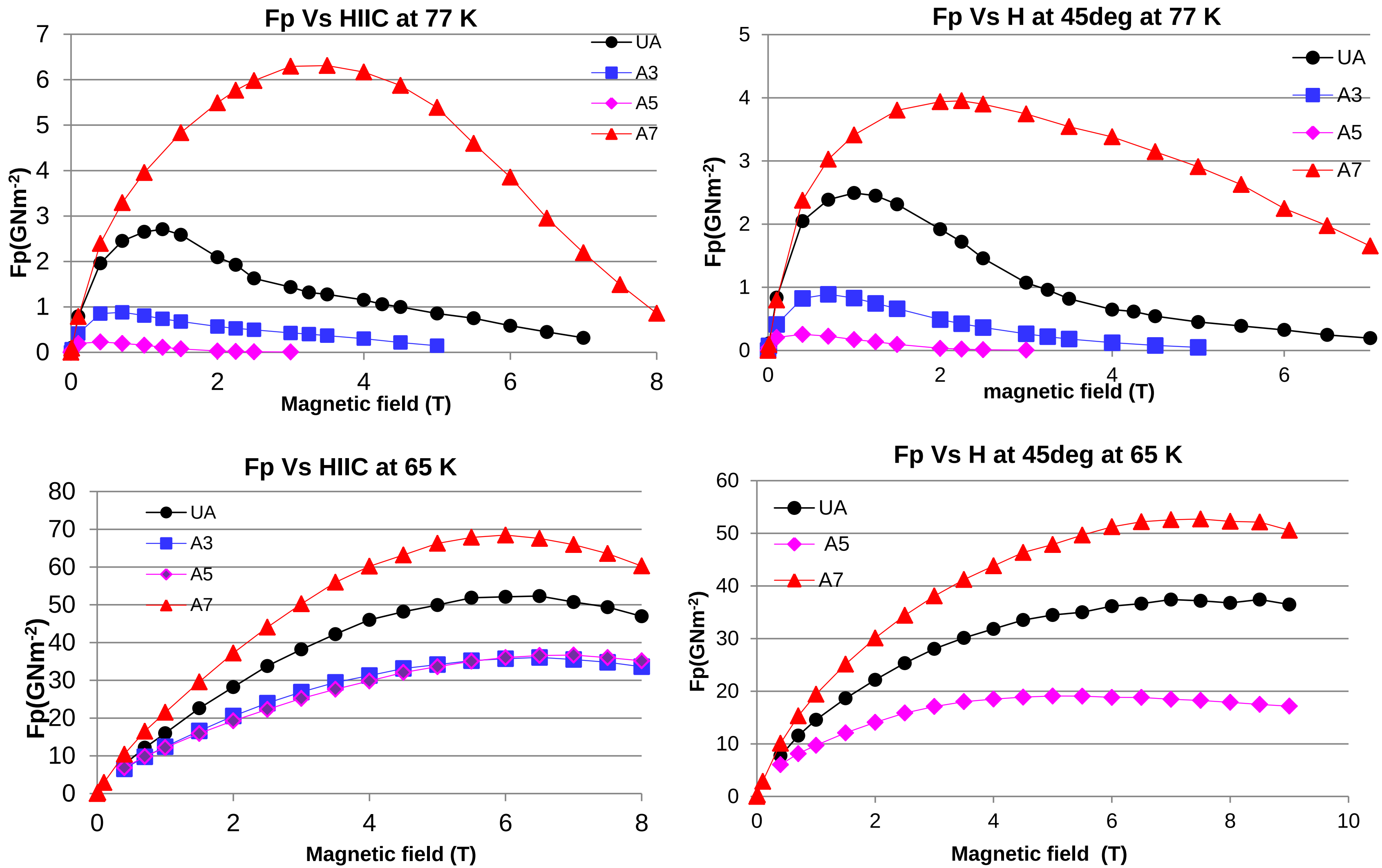
PLD at 790 C followed with post anneal at 825 C

2% BZO/YBCO

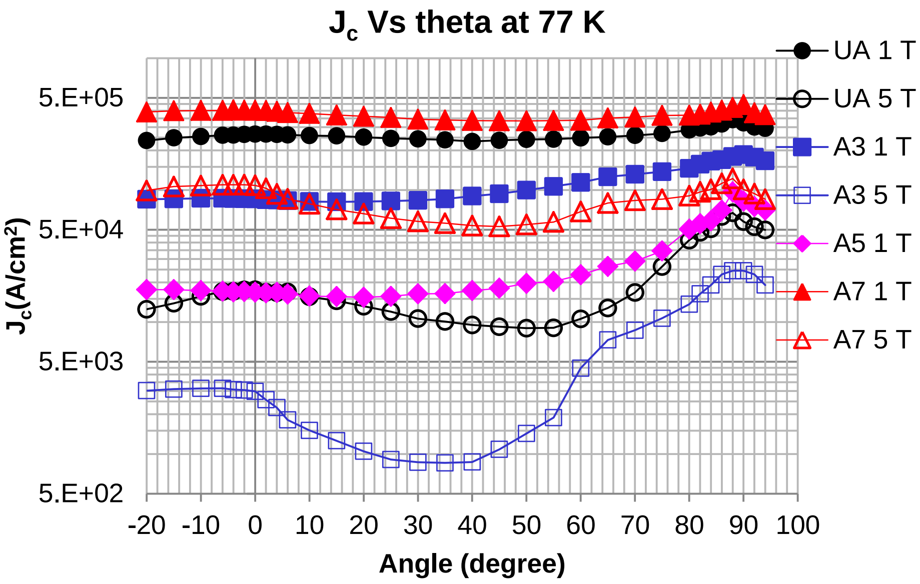


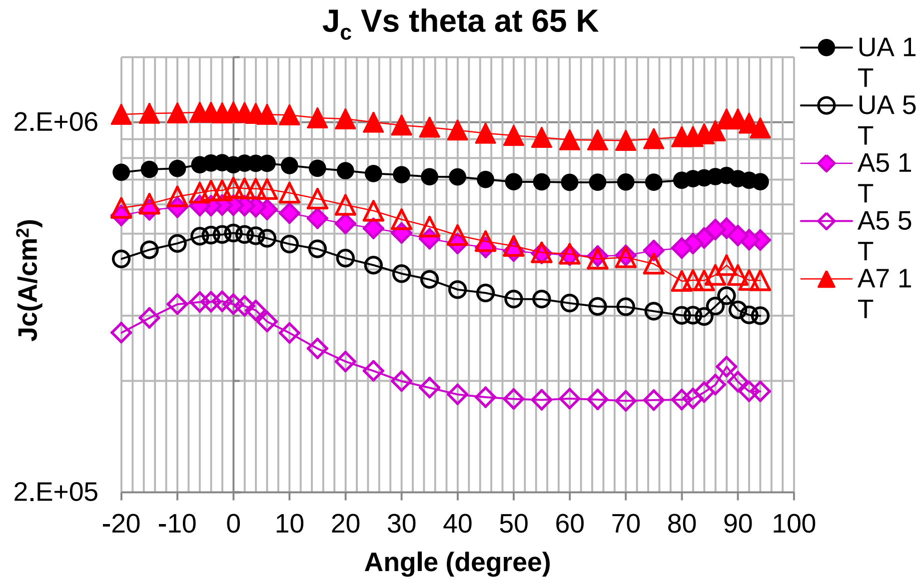
Gautum et al, preprint

Figure 2 a,b,c,d



Post anneal at 825 C promotes growth of weak 0D BZO-APC to strong 3D BZO-APCs





Besides higher J_c and F_p values, strong 3D BZO-APCs also improve isotropic J_c

Gautum et al, preprint

Summary

Understanding the Interfacial strain (local and global) provides means to control APC's morphology, orientation and dimension:

- **Local YBCO/dopant interfacial strain (lattice mismatch, elastic constants) determines the morphology and dimension of the APCs in the YBCO matrix film**
- **Global substrate/film interfacial strain add additional tuning to the APC landscape (nanorod alignment from c-aligned, to splayed, and to ab-aligned)**
- **Controlling interplay between local and global strains allows generation of strong and isotropic BZO APCs using three approaches:**

- **Vicinal + BZO variable concentration**
- **Y_2O_3 +BZO variable concentration**
- **Low T growth BZO/YBCO + high-T post-anneal**