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Micro-straining tuning for strong and isotropic artificial pinning centers (APCs) in YBCO films

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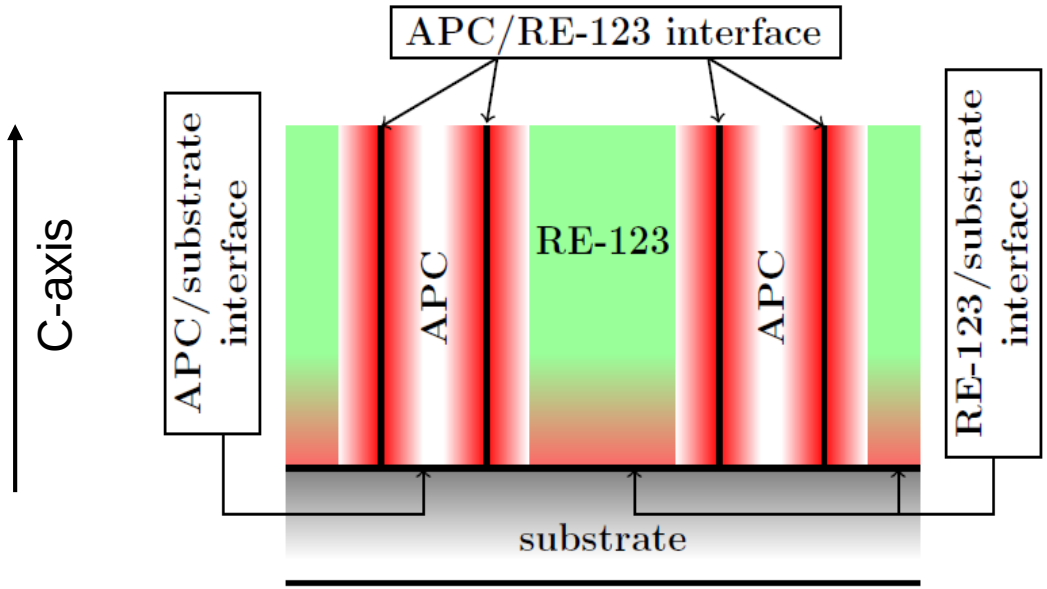
Epitaxial APC/RE-123 nanocomposites



Controlling parameters:

- **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, in SUST Special Issue on Artificial Pinning Centers (2017), DOI:10.1088/1361-6668/aa8288

Understanding the Interplay of strains is important towards controlling APCs

Specific questions:

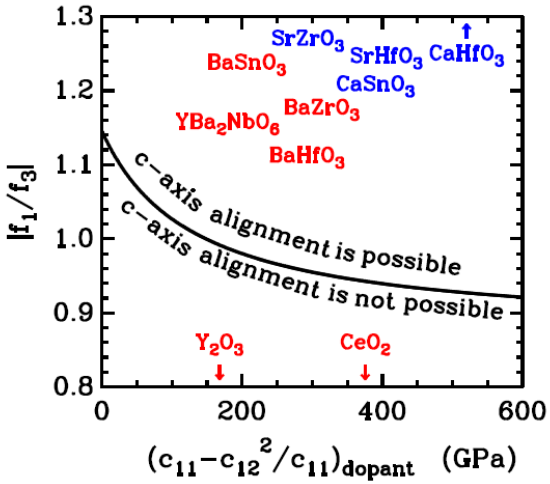
- **Morphology**: What impurity materials will form aligned nanorods (1D APCs) or nanosheets (2D APCs) and nanoparticles (3D APCs) in YBCO matrix?
- **Dimension**: What determines the dimension of the APCs?
- **Orientation**: What determines APC orientations? Is it possible to obtain **mixed** orientations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

Elastic Strain Model + Experiment

Understanding & controlling self-assembly of artificial pinning centers

APC material selection

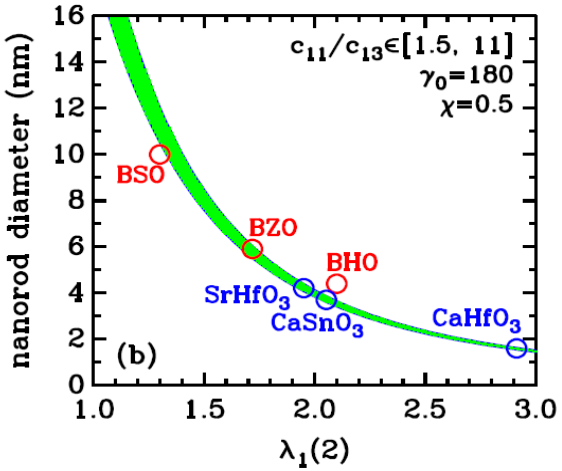
APC morphology can be pre-screened based on their elastic properties & lattice constants



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

APC dimension

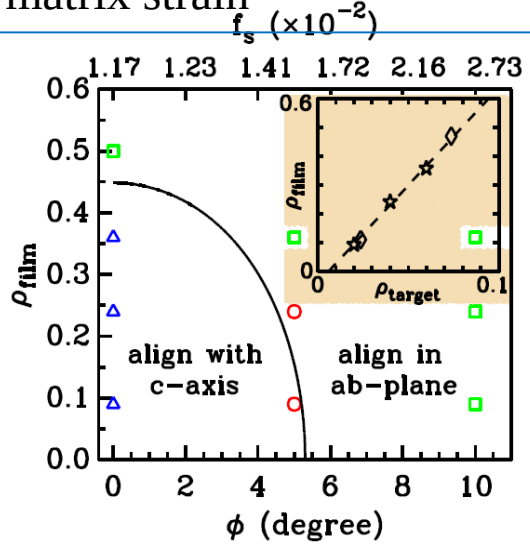
1D APC diameter is determined by the inverse strain decay length $\lambda_1(2)$



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)

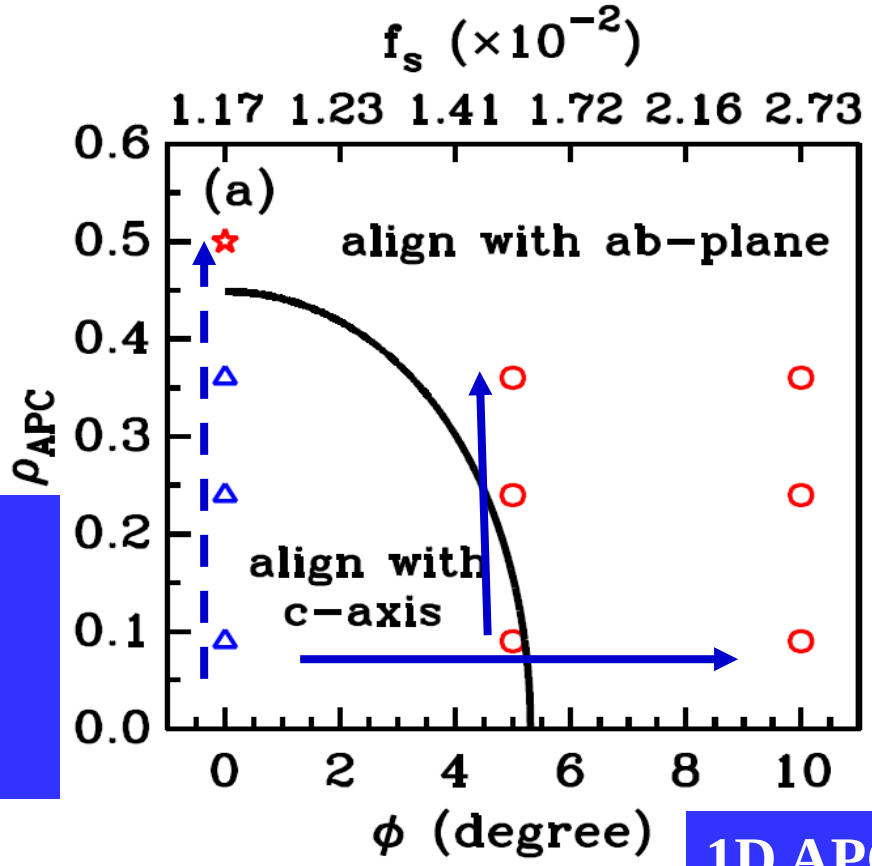
Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017), DOI:10.1088/1361-6668/aa8288

APC orientation vs. YBCO matrix strain

(controlled by RE-123 film/substrate lattice mismatch on vicinal substrate)

Switch of 1D APC orientation

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



Switch of 1D APC orientation

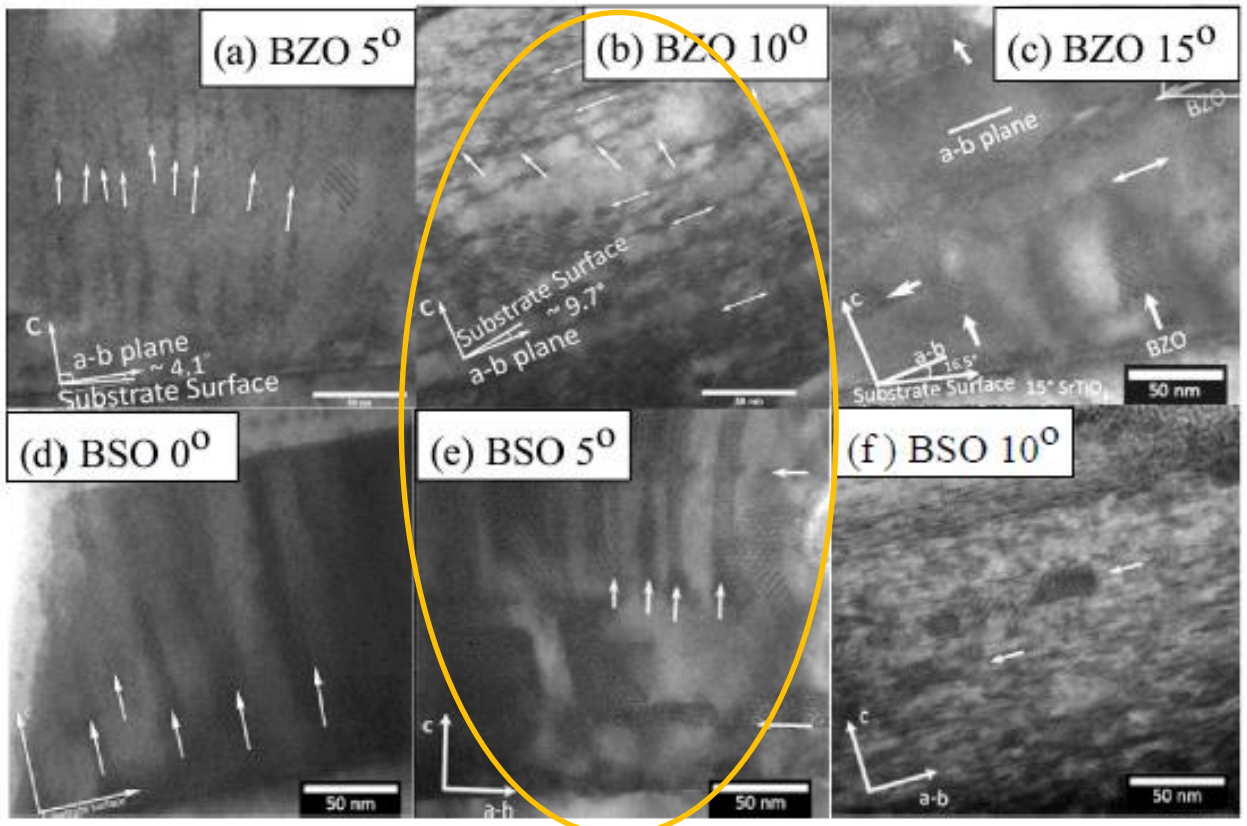
1D APC switch from c-aligned to ab-aligned by introducing lattice mismatched substrates

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).

Increasing YBCO matrix ab-plane tensile strain can cause 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

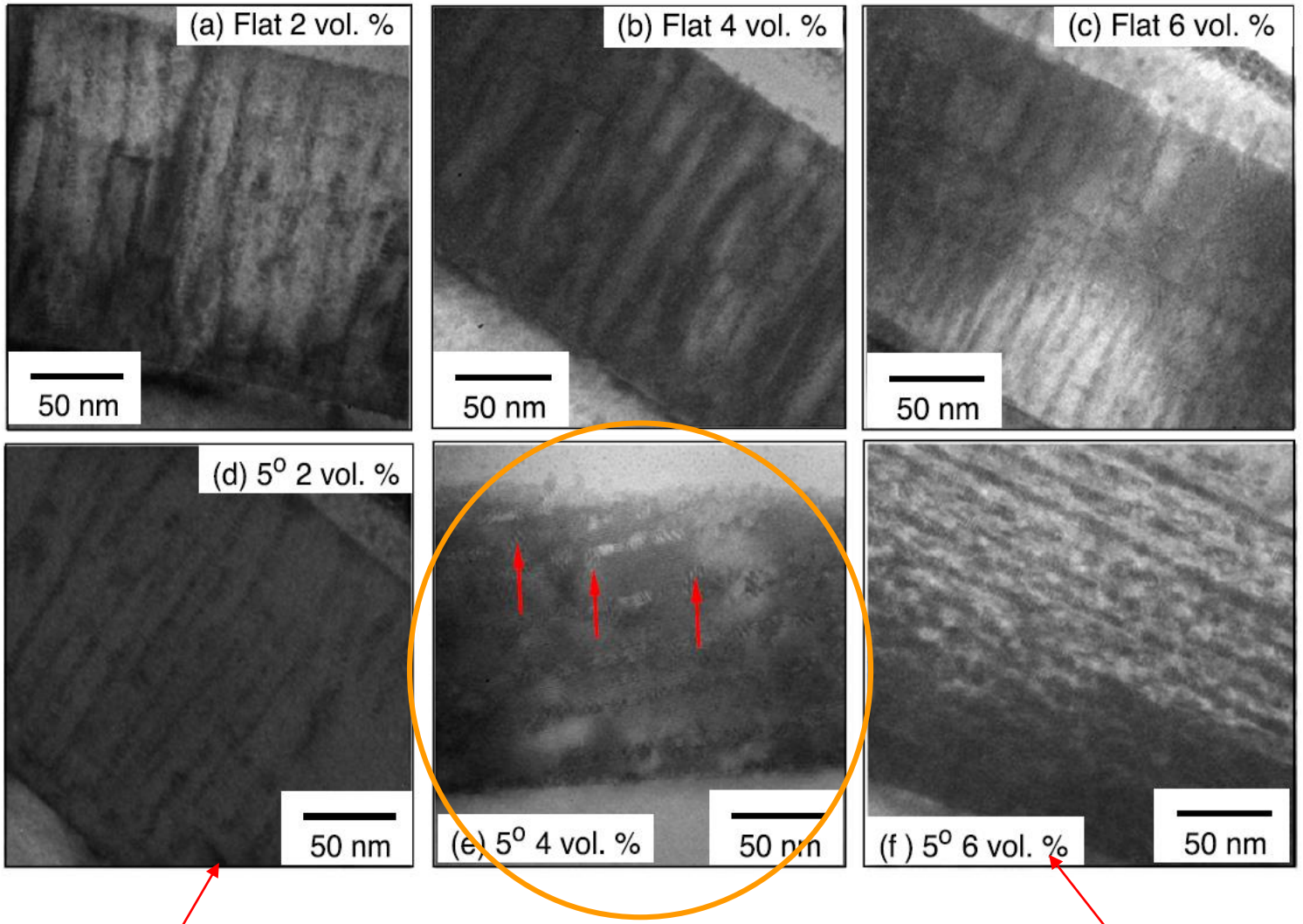
Transition zone with 1D+2D mixed orientations of APCs

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)

Flat STO

5 deg Vicinal STO



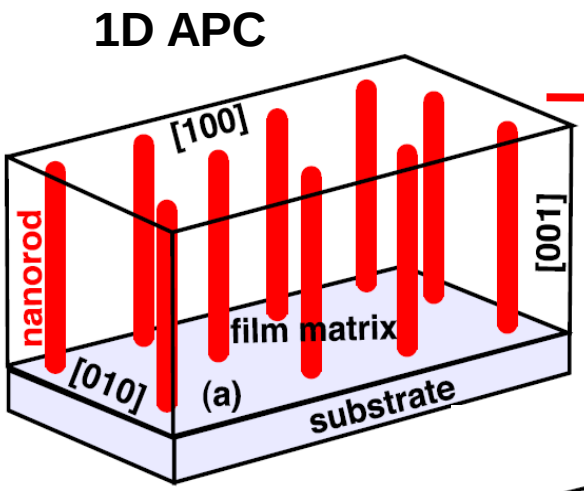
1D (c-axis)

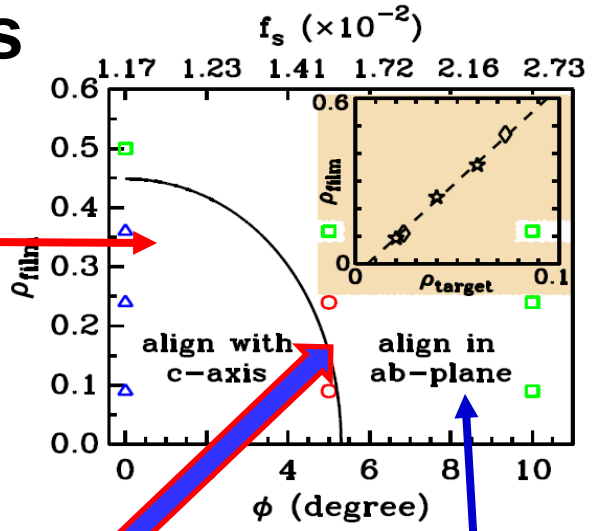
1D (c-axis)+2D APC (ab-plane)

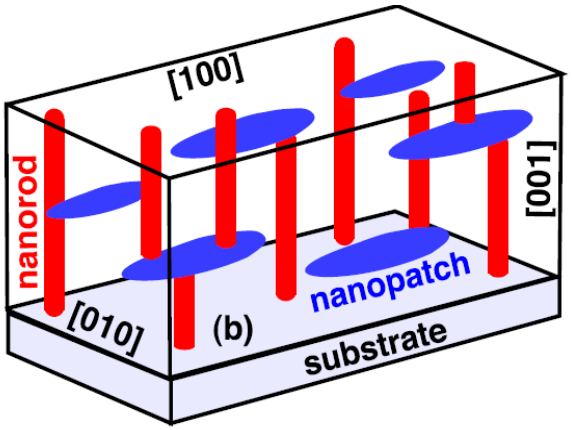
2D APC (ab-plane)

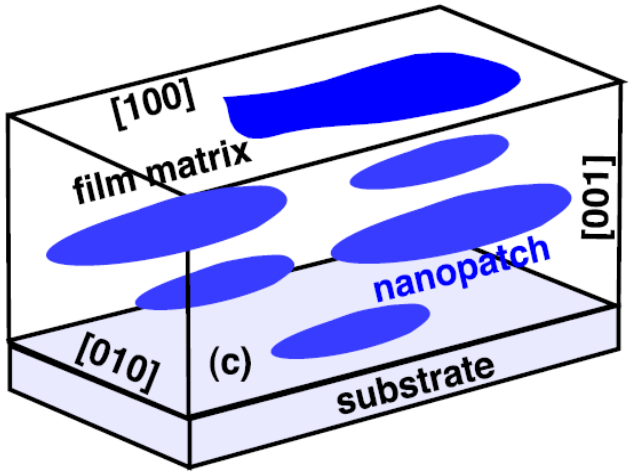
Wu et al, SUST 28, 125009(2015)

Mixed orientations of 1D+2D APCs



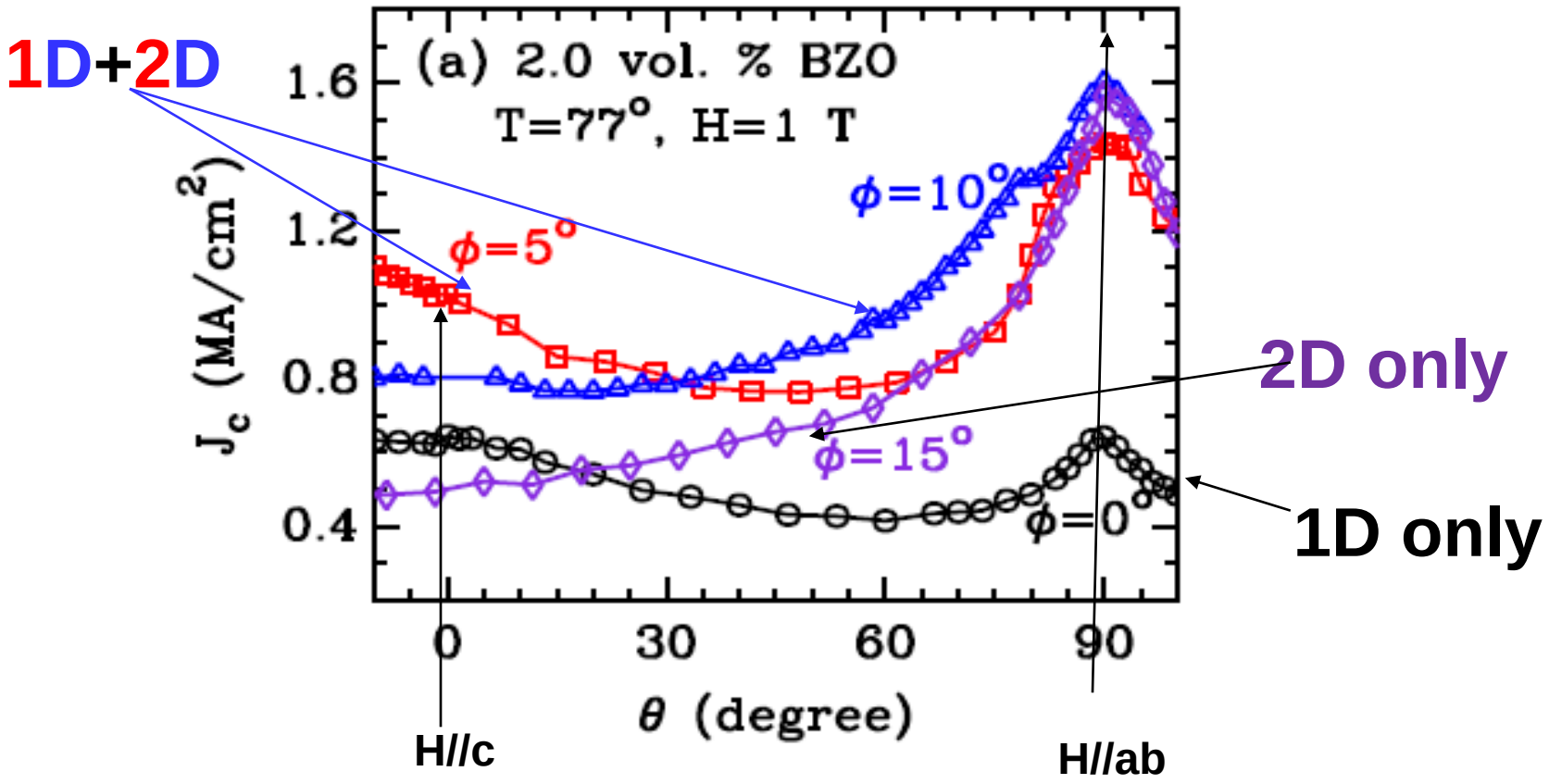




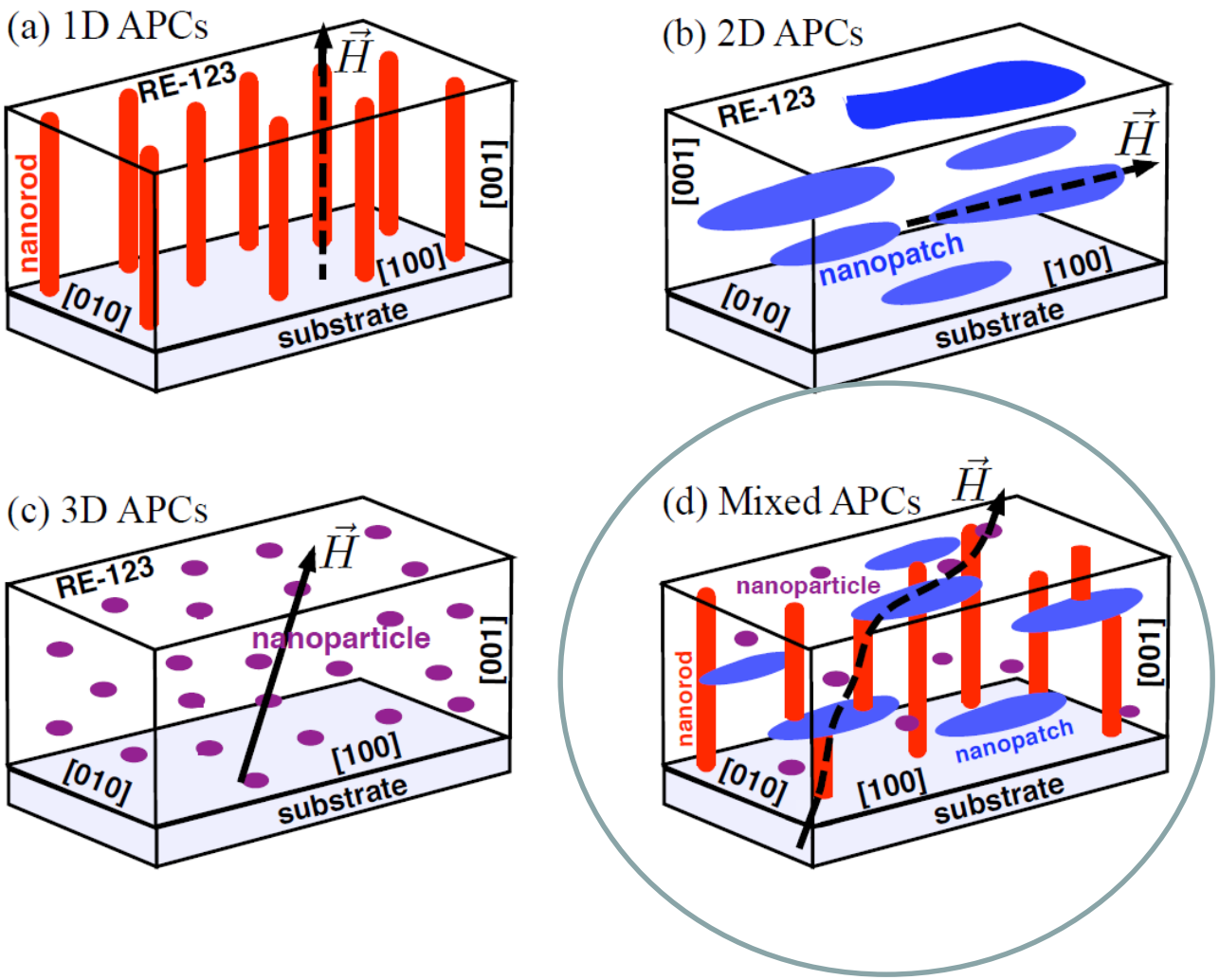


APCs of mixed morphologies can be generated from the same APC material

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

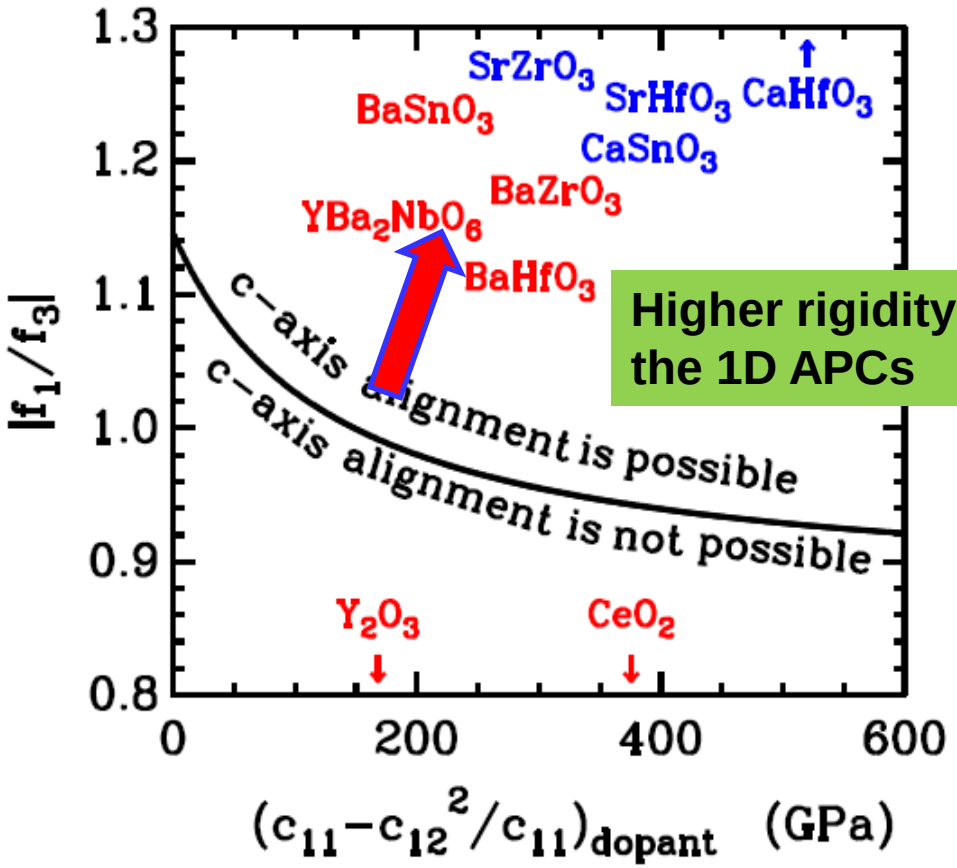


Overall enhanced J_c in all H directions in mixed BZO APC/YBCO possibly due to 1) reduced strain on YBCO; 2) mixed orientations of BZO APCs



1D+2D+3D mixed APCs

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



Higher rigidity of the 1D APCs

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:

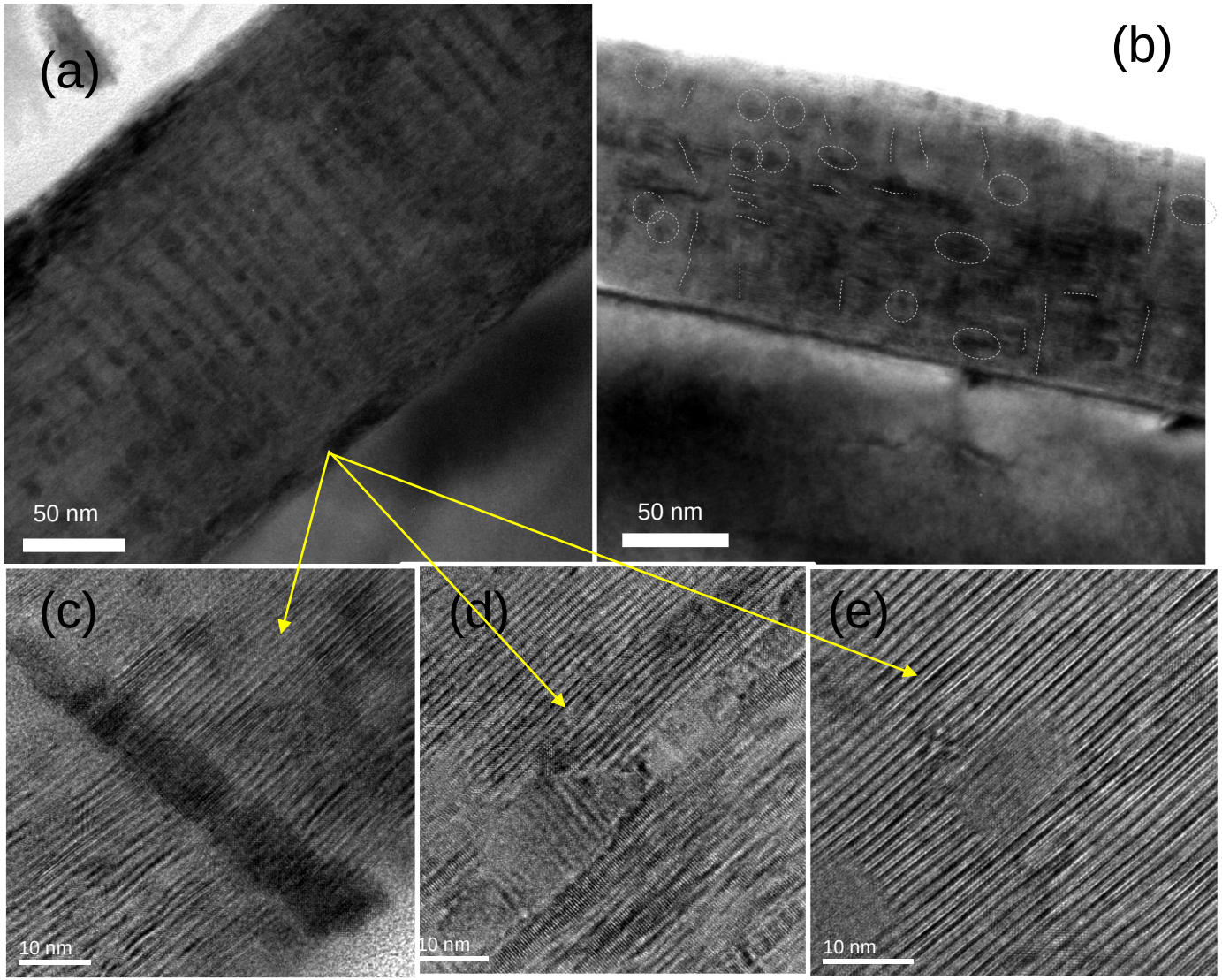
BHO (BZO) + Y2O3:

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.

Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017), DOI:10.1088/1361-6668/aa8288

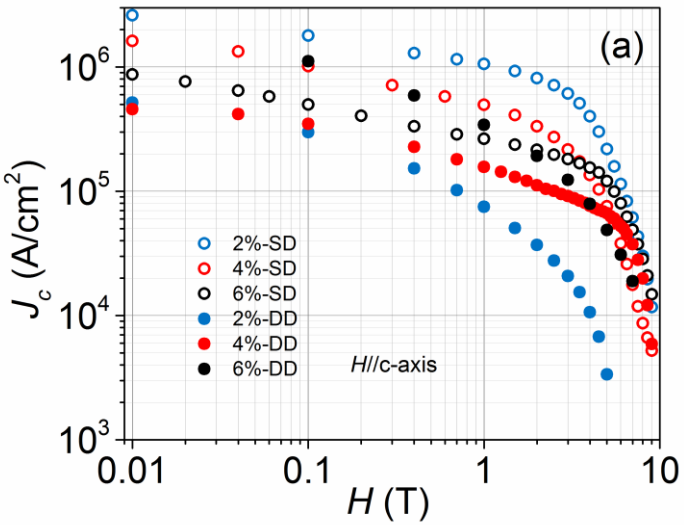
4 vol % BZO+3 vol % Y_2O_3 6 vol % BZO+3 vol % Y_2O_3



1D APC **2D APCs** **3D APCs**

Chen et al, submitted to SUST

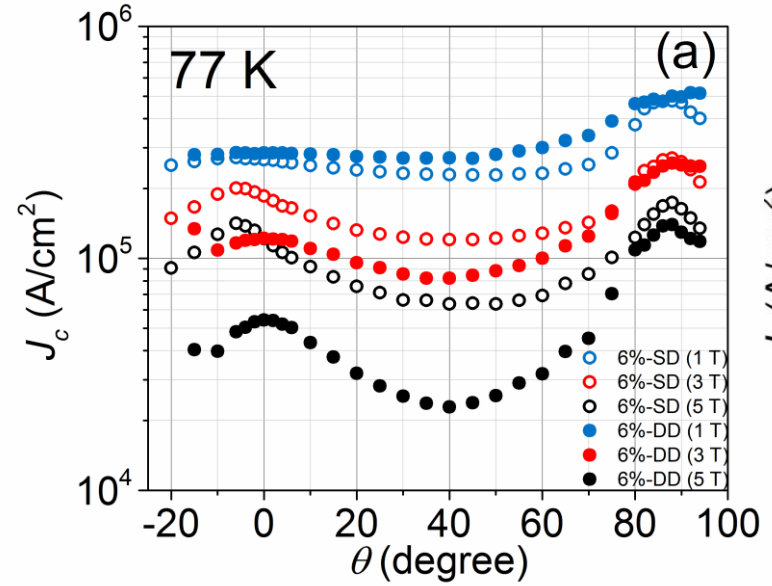
Opposite trends in J_c of DD (BZO+Y_2O_3) and SD (BZO only) with BZO APC concentration

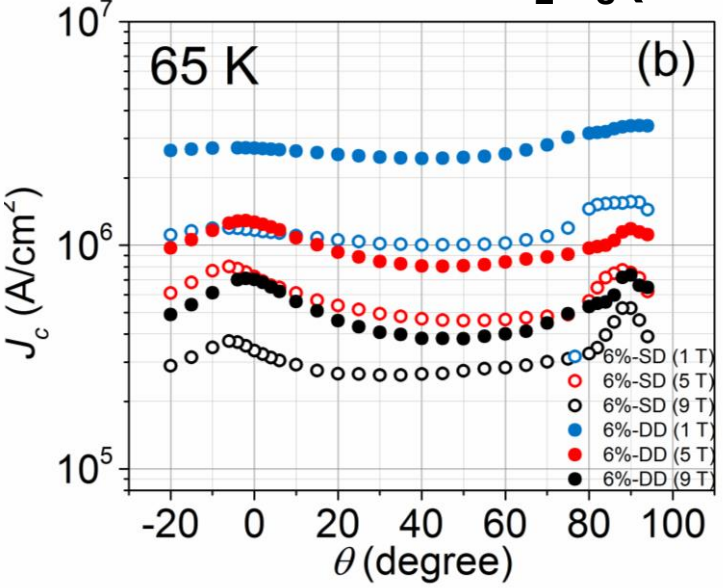


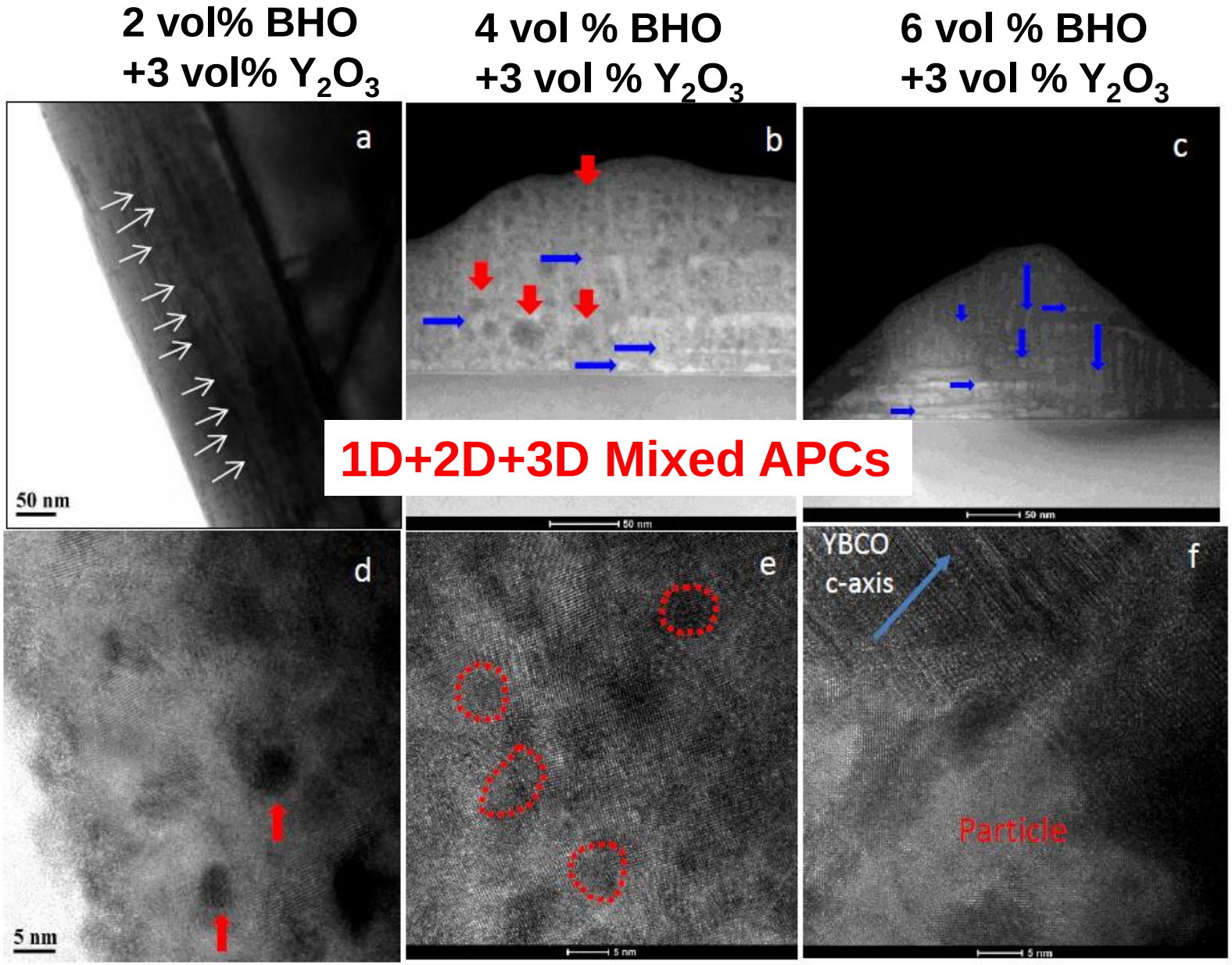
Chen et al, IEEE Transaction on Applied Superconductivity Vol. 27, 2017;
Chen et al, submitted to SUST

Reduced J_c anisotropy in DD samples

6 vol % BZO (open) vs. 6 vol%BZO +3 vol % Y_2O_3 (solid)

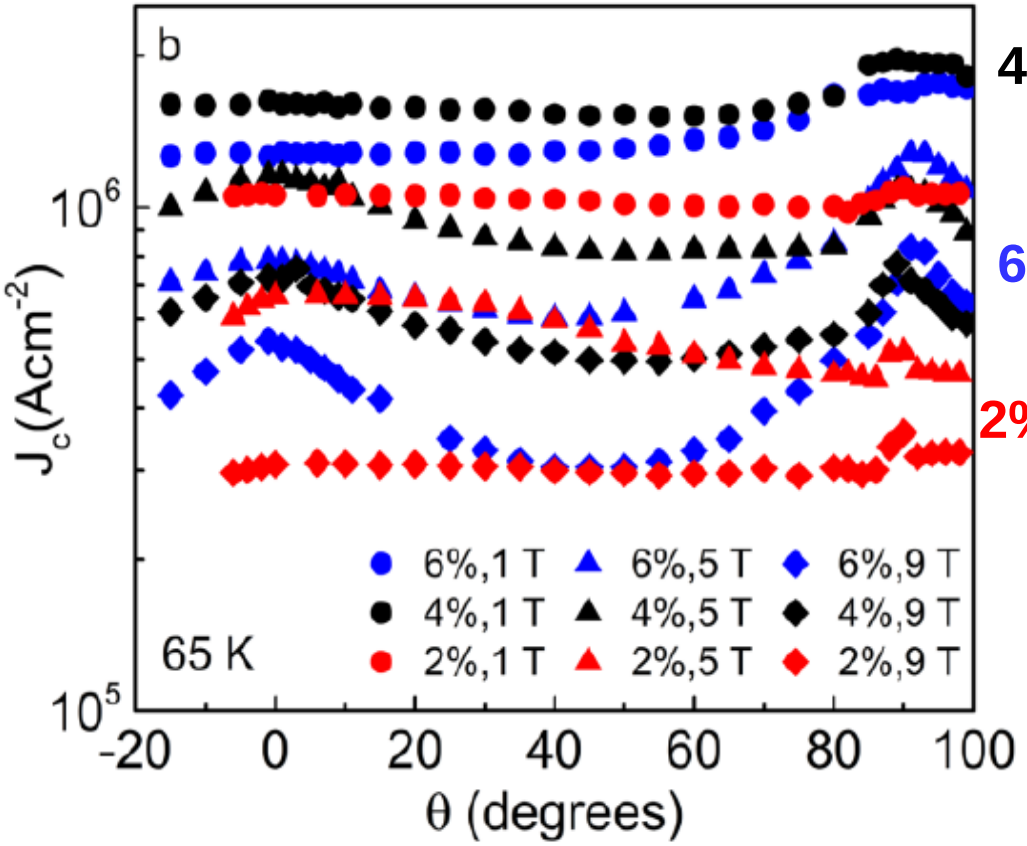






B. Gautam et al, *AIP Advances*, 7 (7), 0753082017;Gautam et al, manuscript in preparation

2-6 vol% BHO +3 vol % Y_2O_3



4% BHO DD

6% BHO DD

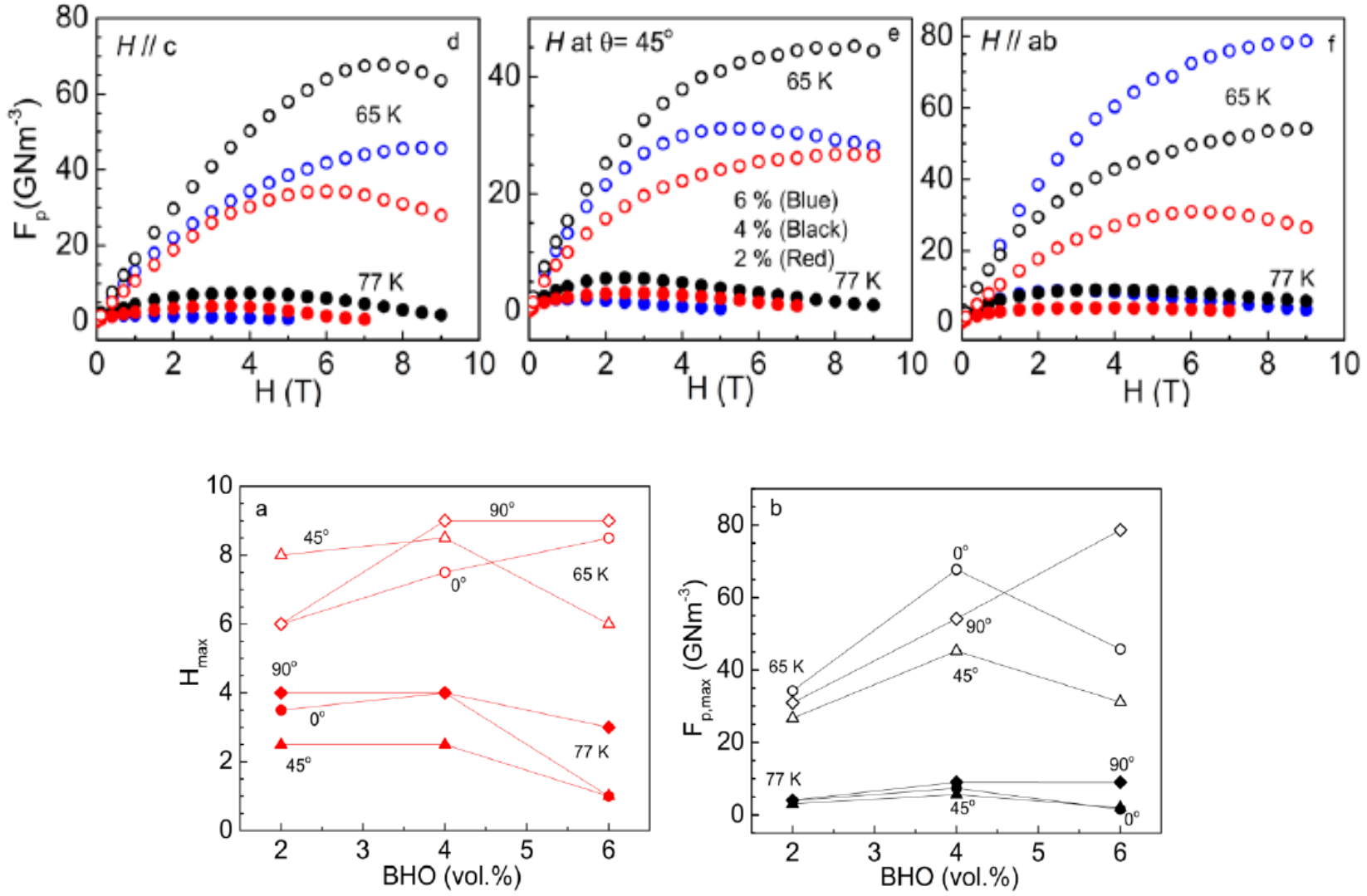
2% BHO DD

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), 0753082017;

Gautam et al, manuscript in preparation

2-6 vol% BHO +3 vol % Y_2O_3 (open-65K, solid-77K)



4% BHO DD shows the best Jc, and smallest angu
More ab-aligned APCs at 6% BHO DD

B. Gautam et al, *AIP Advances*, 7 (7), 0753082017;Gautam et al, manuscript in preparation

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**