IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019.
Invited presentation 1MOr2C-01 was given at ASC 2018, October 28-November 02, 2018, Seattle (USA).

Probing the Effect of Interface on Pinning Efficiency of 1D $BaZrO_3$ and $BaHfO_3$ Artificial Pinning Centers in $YBa_2Cu_3O_{7-x}$ Thin Films

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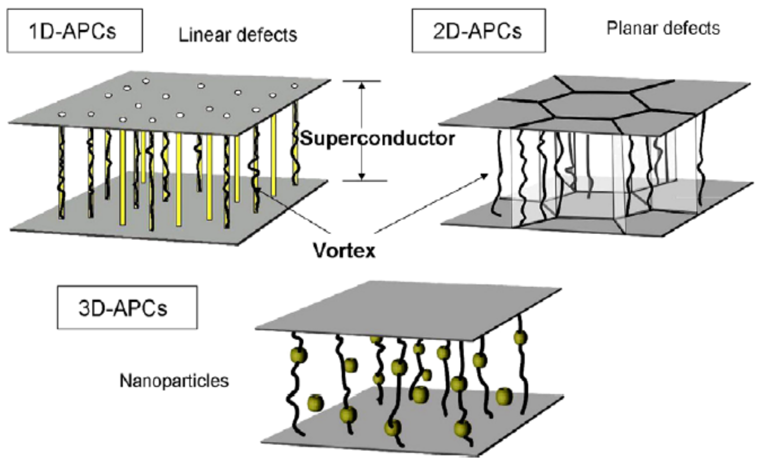
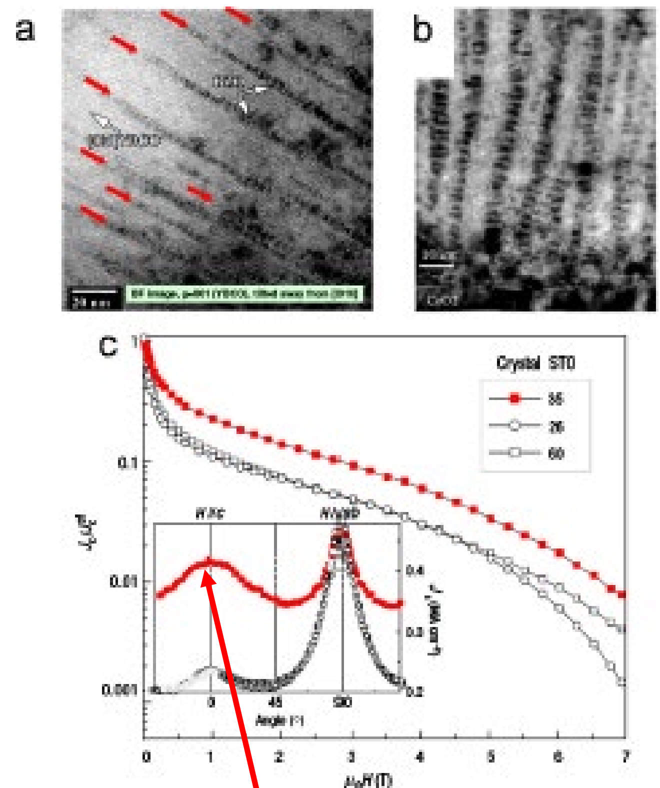
Sponsored by NSF and AFOSR

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

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





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

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

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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 (J_cs) 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

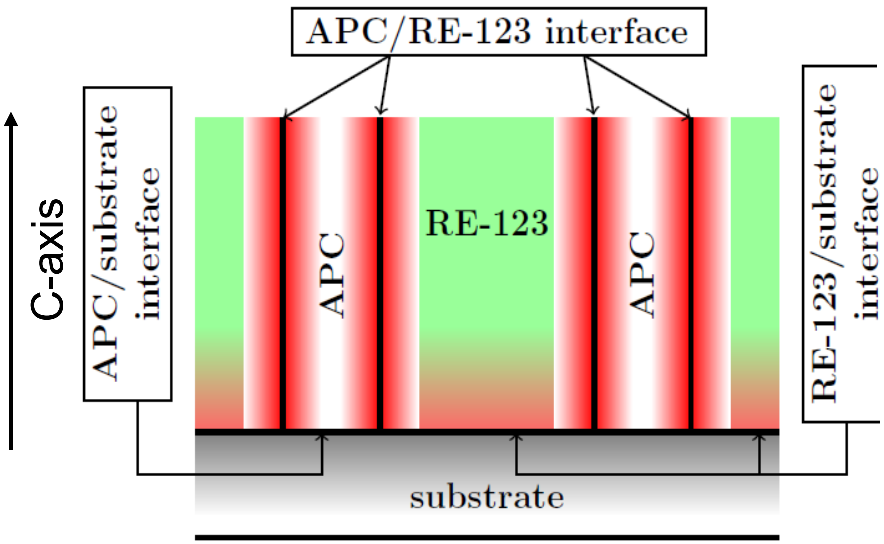
http://iopscience.iop.org/journal/0953-2048/page/Focus-on-Artificial-Pinning-Centers-in-Superconductors

Controlling self-assembly of APCs in APC/HTS nanocomposites

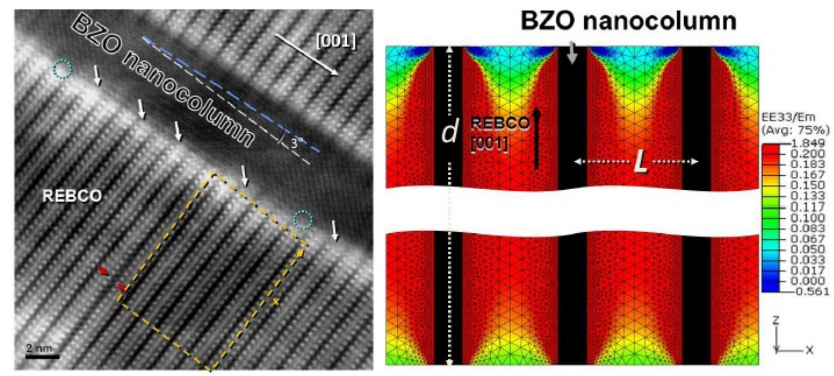
Specific questions:

- **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



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

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

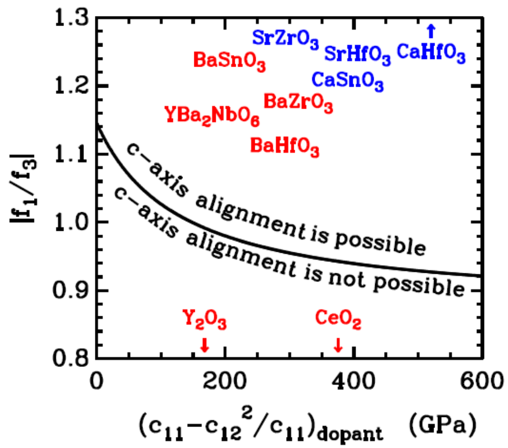
APC morphology can be pre-screened based on their elastic properties & lattice constants

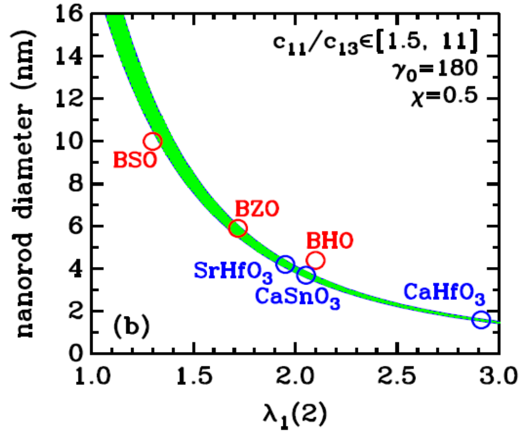
APC dimension

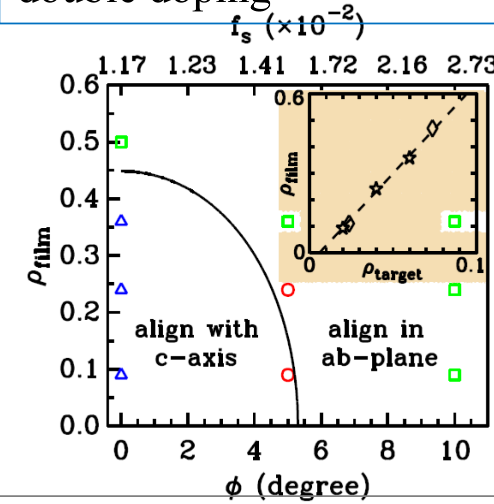
1D APC diameter is determined by the inverse strain decay length $\lambda_1(2)$

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

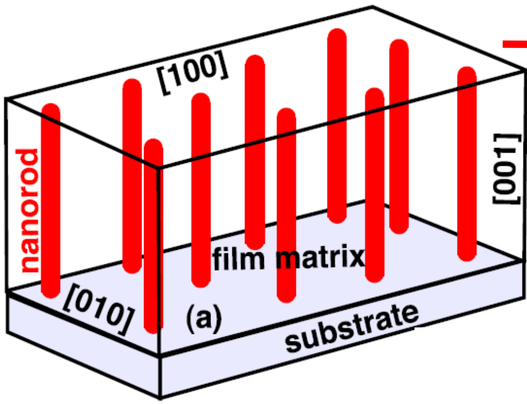
J. Wu, et al, *SUST* **27**, 044010 (2014); Shi and Wu, JAP **118**, 164301 (2015).

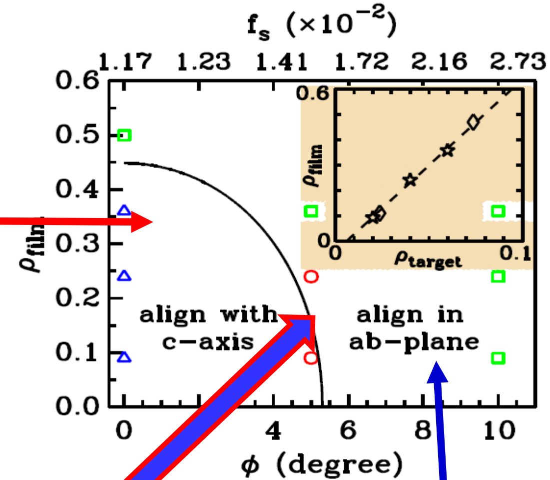
F.J. Baca, et al, Advanced Functional Materials 23, 4628, (2013); J. Wu, et al, *IEEE Trans. Applied Superconductivity* **25** (3), 1-5 (2015); Wu et al, SUST 28, 125009(2015); B. Gautam et al, AIP Advances **7**, 075308 (2017); SUST 31, 025008 (2017); Chen et al, IEEE Trans. Appl. Supercond 27 (4), 4-8 (2017); SUST **30**, 125011 (2017)

Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017), Vol. 30, 103002 (2017)

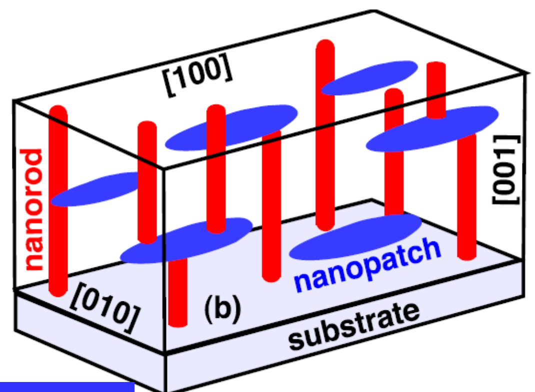
Mixed 1D+2D APCs

1D APC

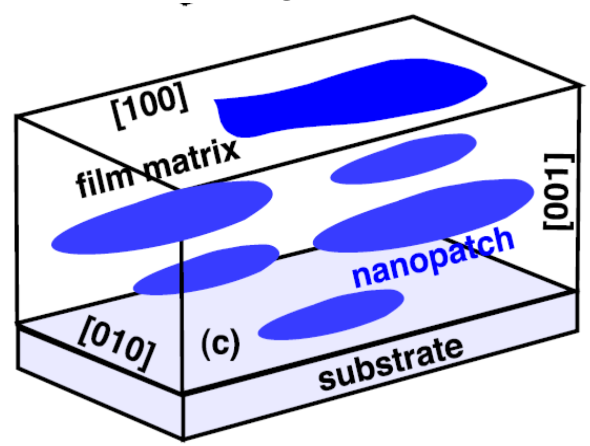




1D+2D APC



2D APC

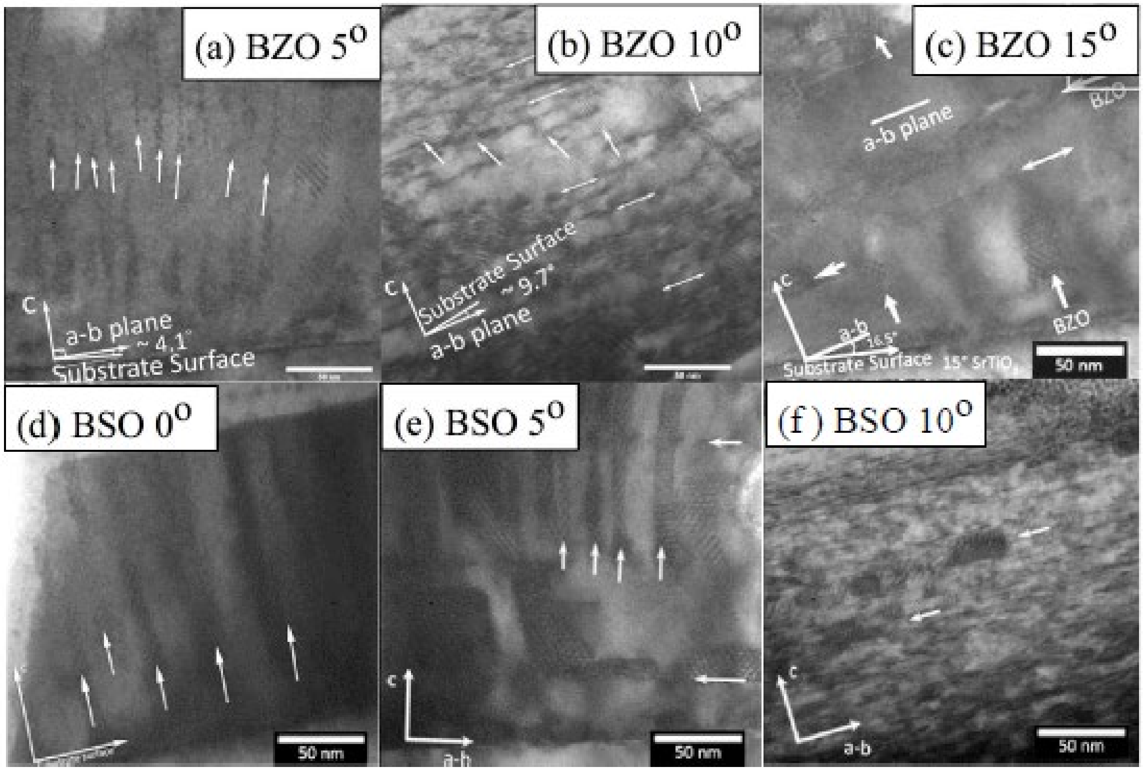


APCs of mixed morphologies can be generated from the same APC material

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

BZO doping

BSO doping



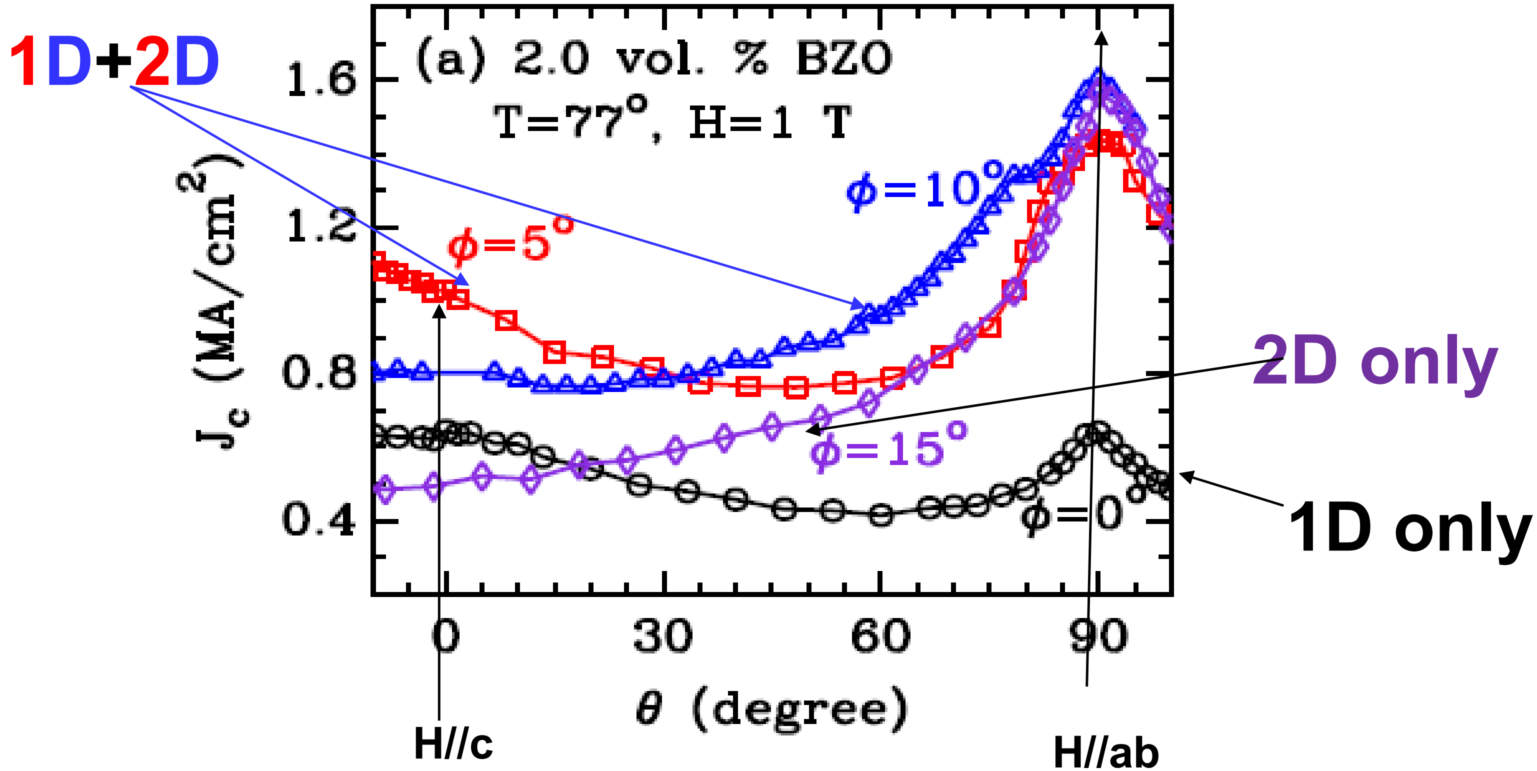
Tensile strain in c-axis

Transition zone with mixed 1D+2D 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)

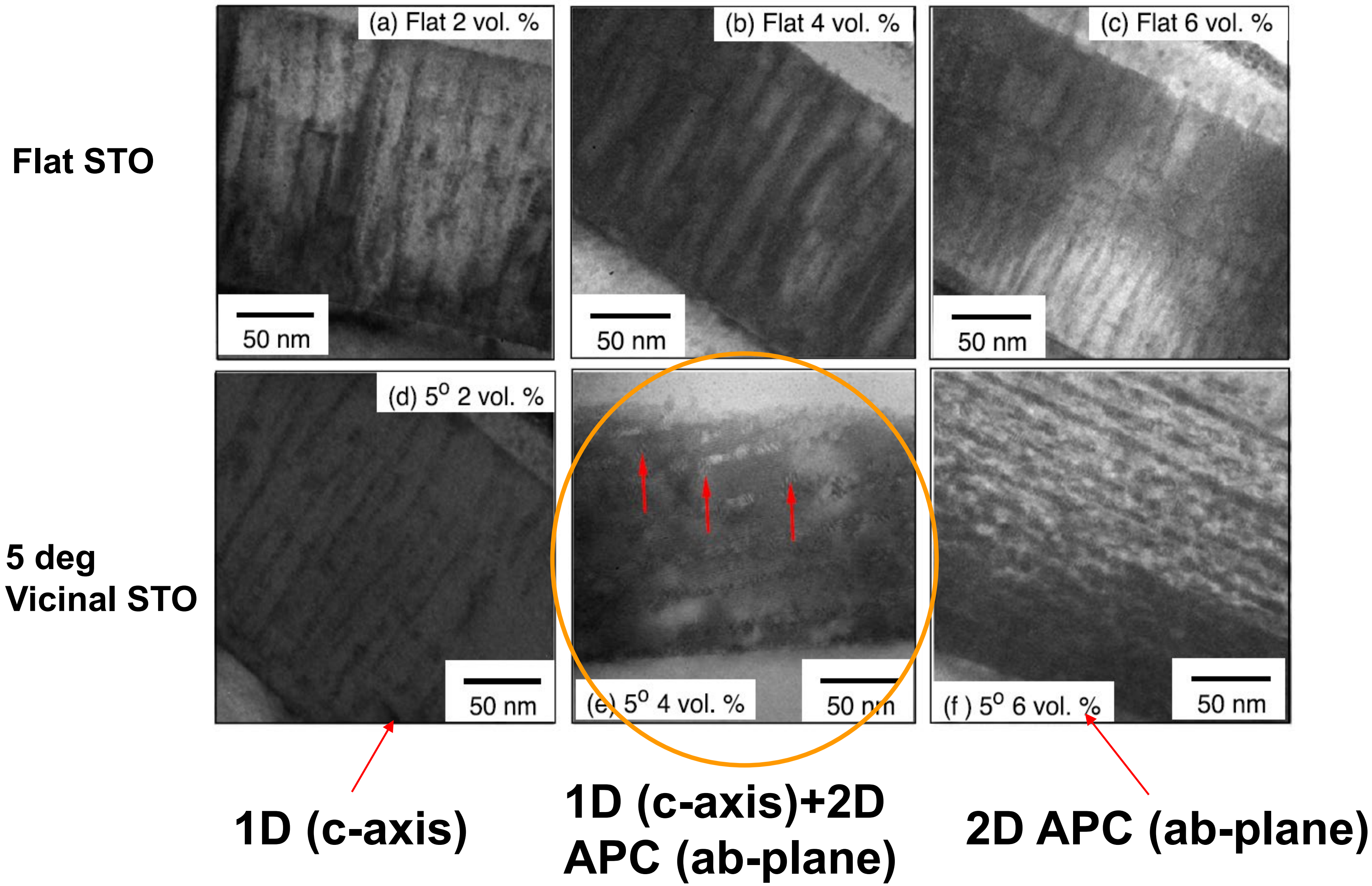
Benefits of mixed 1D+2D APCs: enhanced J_c



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

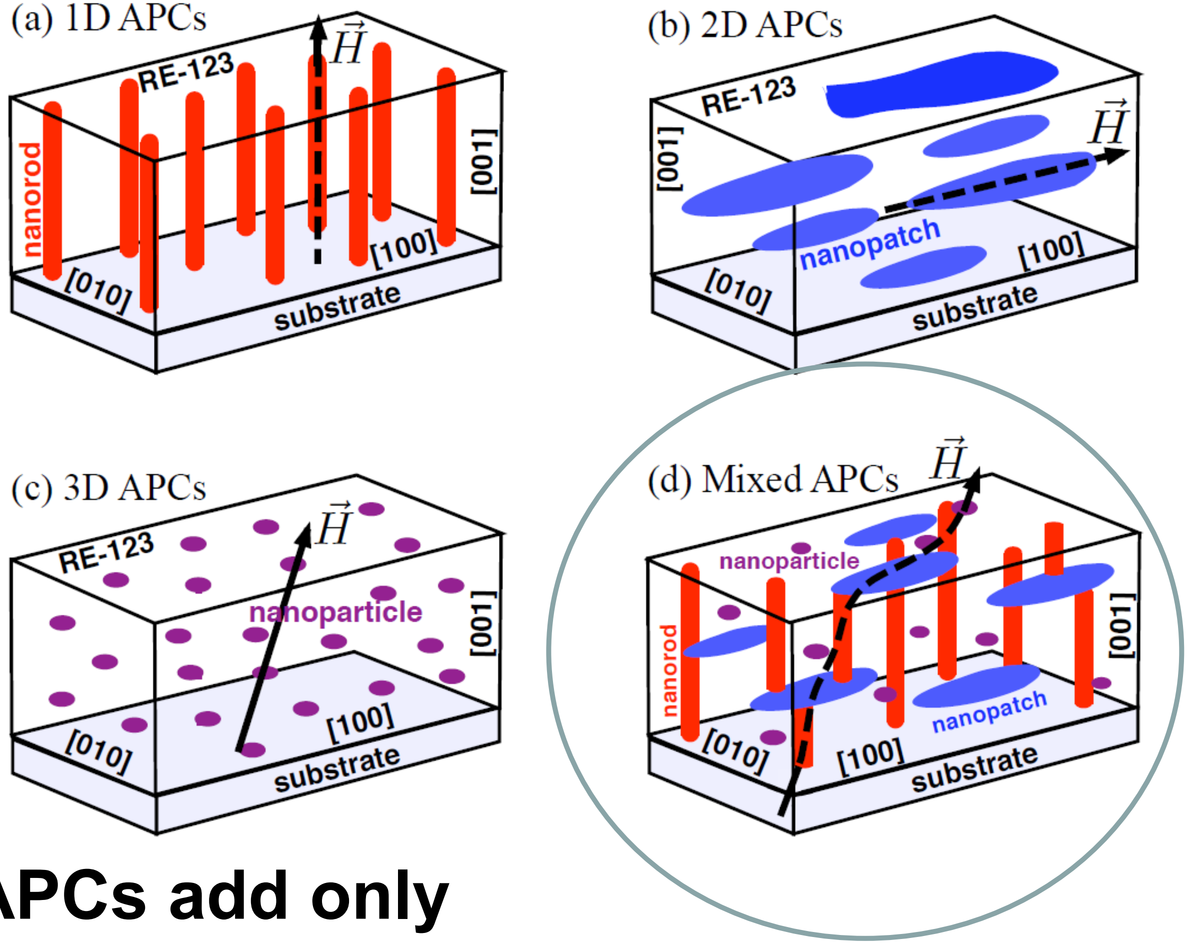
J. Wu, et al., *IEEE Trans. Applied Superconductivity* **25** (3), 1-5 (2015)

Difficult to obtained mixed 1D+2D APCs



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

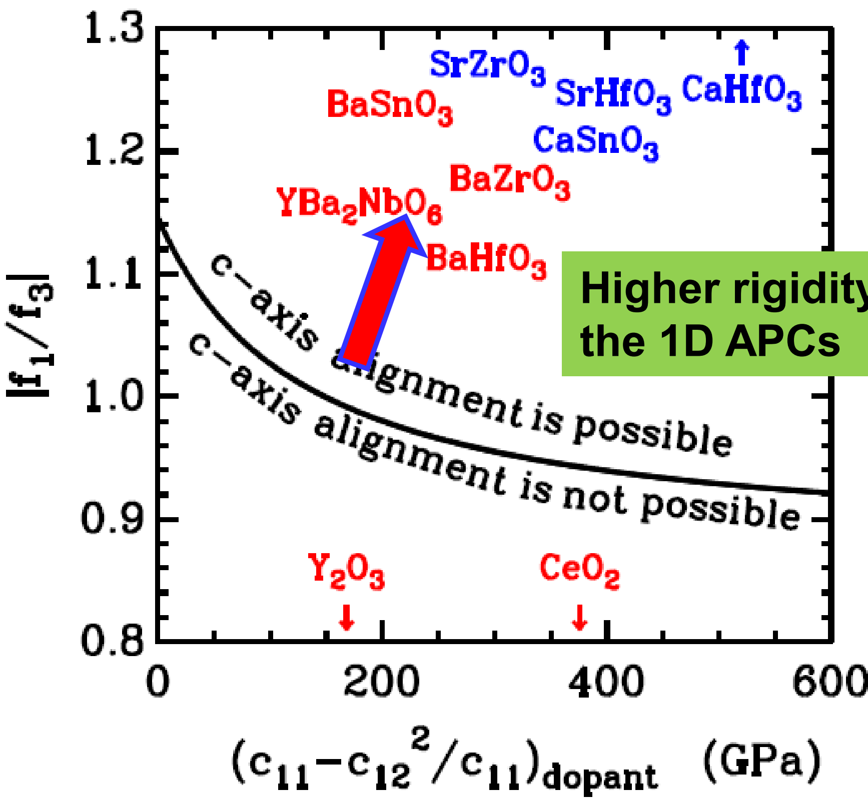
Mixed 1D+2D+3D APCs



3D APCs add only local perturbation of the strain field

1D+2D+3D mixed APCs

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



1D APCs with higher rigidity:

BSO + Y2O3:

1D + 3D APCs

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

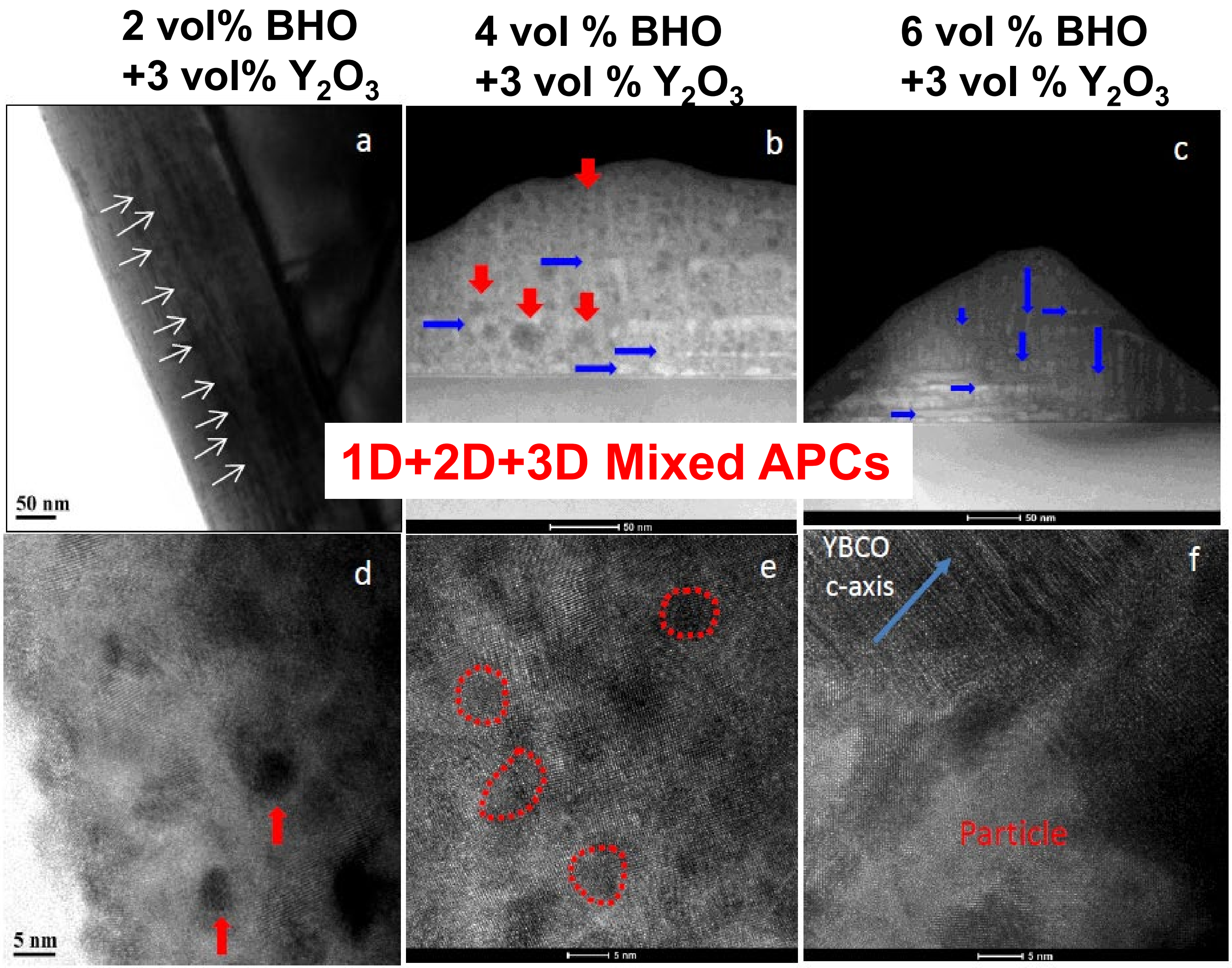
1D APCs with lower rigidity:

BHO (BZO) + Y2O3:

1D + 2D + 3D APCs

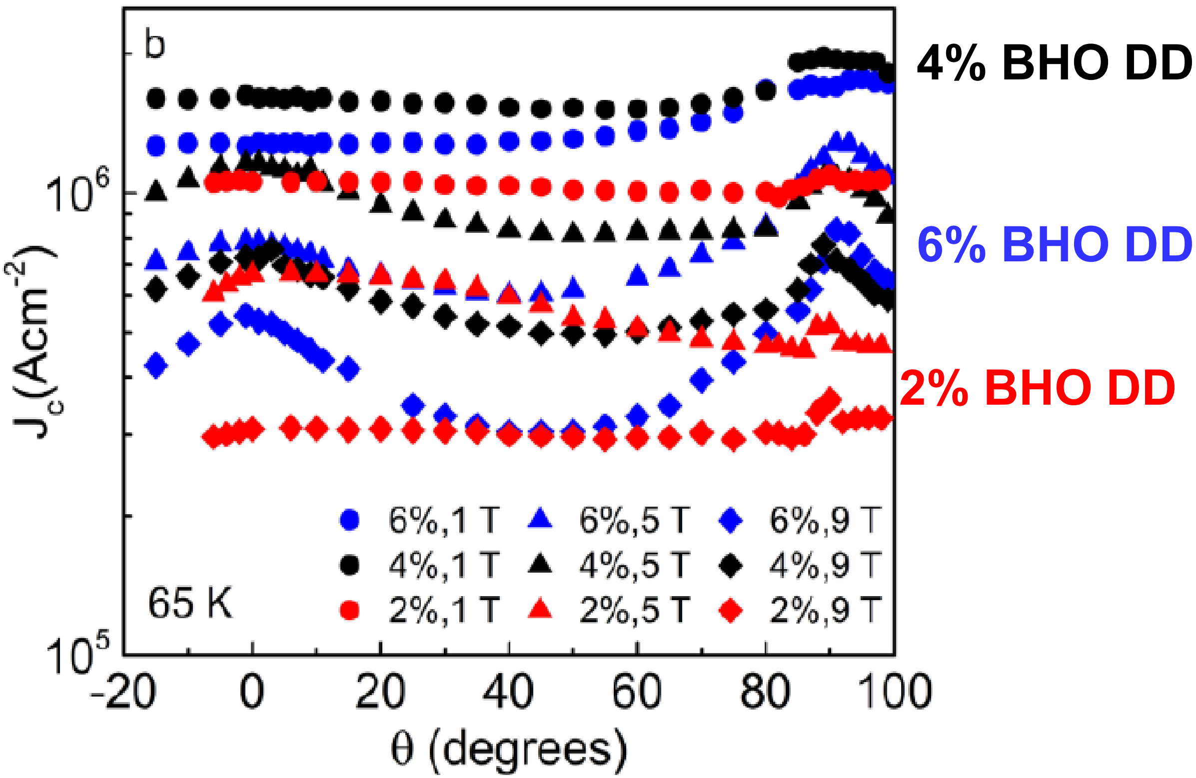
B. Maiorov, et al. *Nature Mat.* (2009); M. A. P. Sebastian, et al., "IEEE Trans on Appl Supercond, vol. 27, pp. 1-5, 2017.

Wu and Shi, in SUST Special Issue on Artificial Pinning Centers (2017), Vol. 30, 103002 (2017); B. Gautam et al., AIP Advances 7, 075308 (2017); SUST 31, 025008 (2017); Chen et al., IEEE Trans. Appl. Supercond 27 (4), 4-8 (2017); SUST 30, 125011 (2017)



B. Gautam et al., *AIP Advances*, 7 (7), 0753082017; Gautam et al., SUST 31, 025008 (2017)

2-6 vol% BHO +3 vol % Y_2O_3



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)

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

Specific questions:

Morphology and dimension

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- **Pinning Efficiency of 1D APCs:** Understanding the effect of APC/YBCO interface on the individual pinning efficiency

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

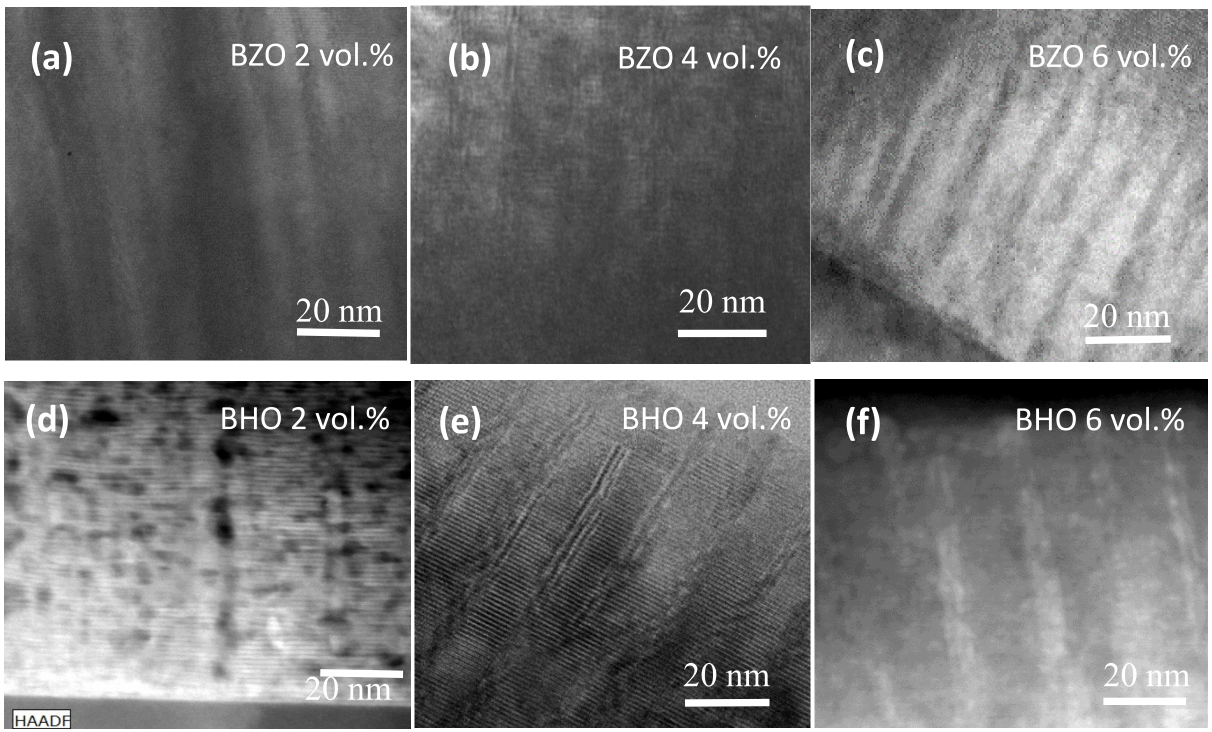
H_{max}--location of the F_p maximum

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

F_p (H) =J_cxH—pinning force density

$F_{p,max}$—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



BZO
2,4, 6vol.%

BHO
2,4, 6vol.%

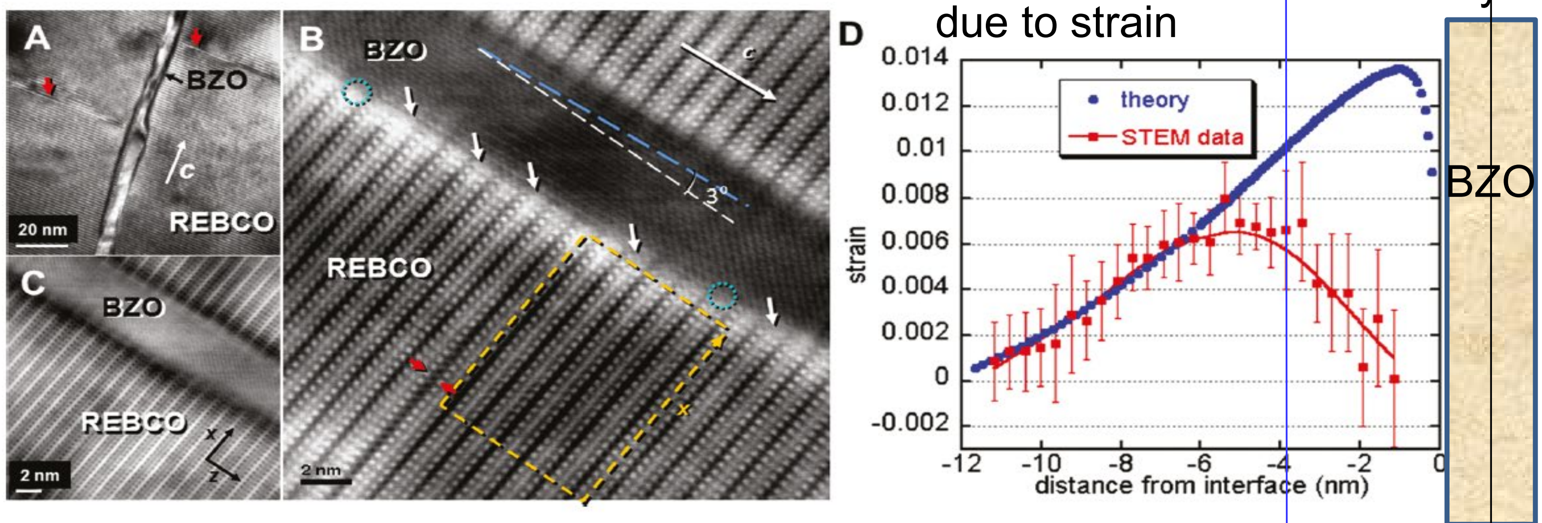
	Sample ID	T_c (K)	C-axis lattice constant (Å)	FWHM of YBCO (005) peak	D (nm)	d (nm)	H^* (T)	Lattice mismatch with *c*-axis of YBCO
BZO 2-6 vol.%	2 vol.% BZO/YBCO	89.27	11.82	0.35	5.2	20	5.0	7.7%
	4 vol.% BZO/YBCO	87.48	11.71	0.34	5.8	15	9.2	
	6 vol.% BZO/YBCO	86.90	11.67	0.27	5.9	12	14.3	
BHO 2-6 vol.%	2 vol.% BHO/YBCO	88.85	11.77	0.42	5.0	30	2.0	7.1%
	4 vol.% BHO/YBCO	85.84	11.77	0.51	5.0	13	12.2	
	6 vol.% BHO/YBCO	78.50	11.78	0.49	5.0	16	8.0	

- **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**

C. Cantoni et al., ACS Nano 5, 4783, (2011)

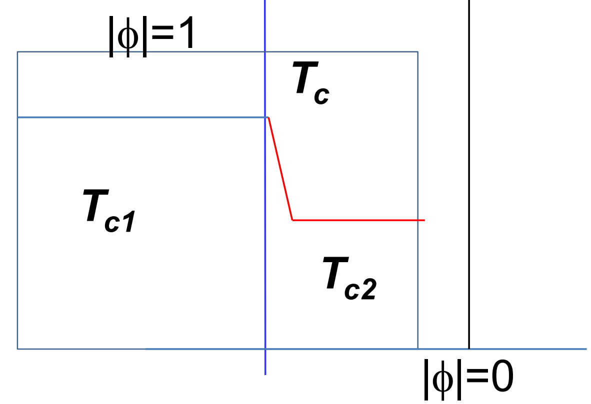
YBCO column With reduced Tc due to strain

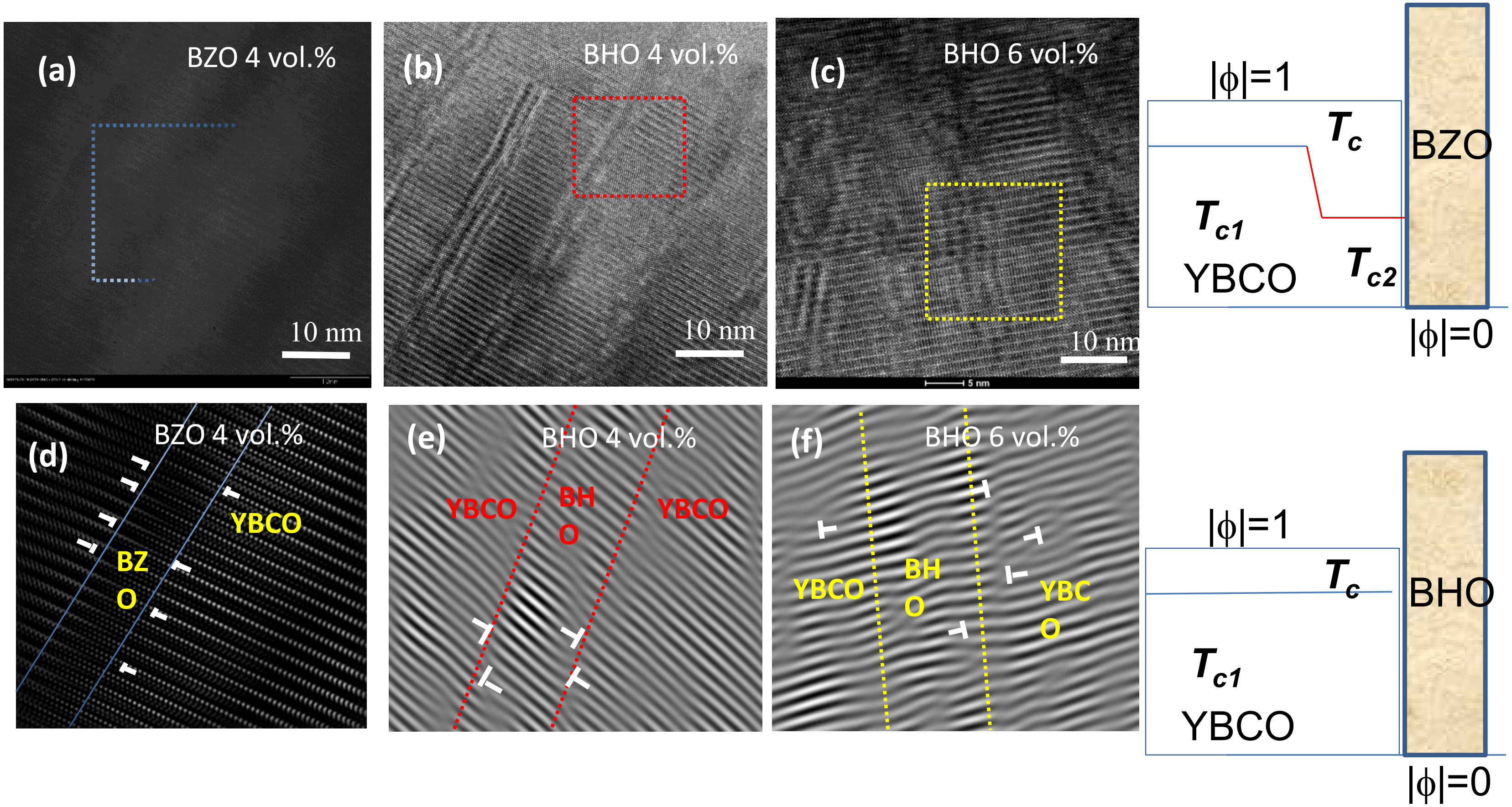
YBCO column with reduced Tc due to oxygen deficiency



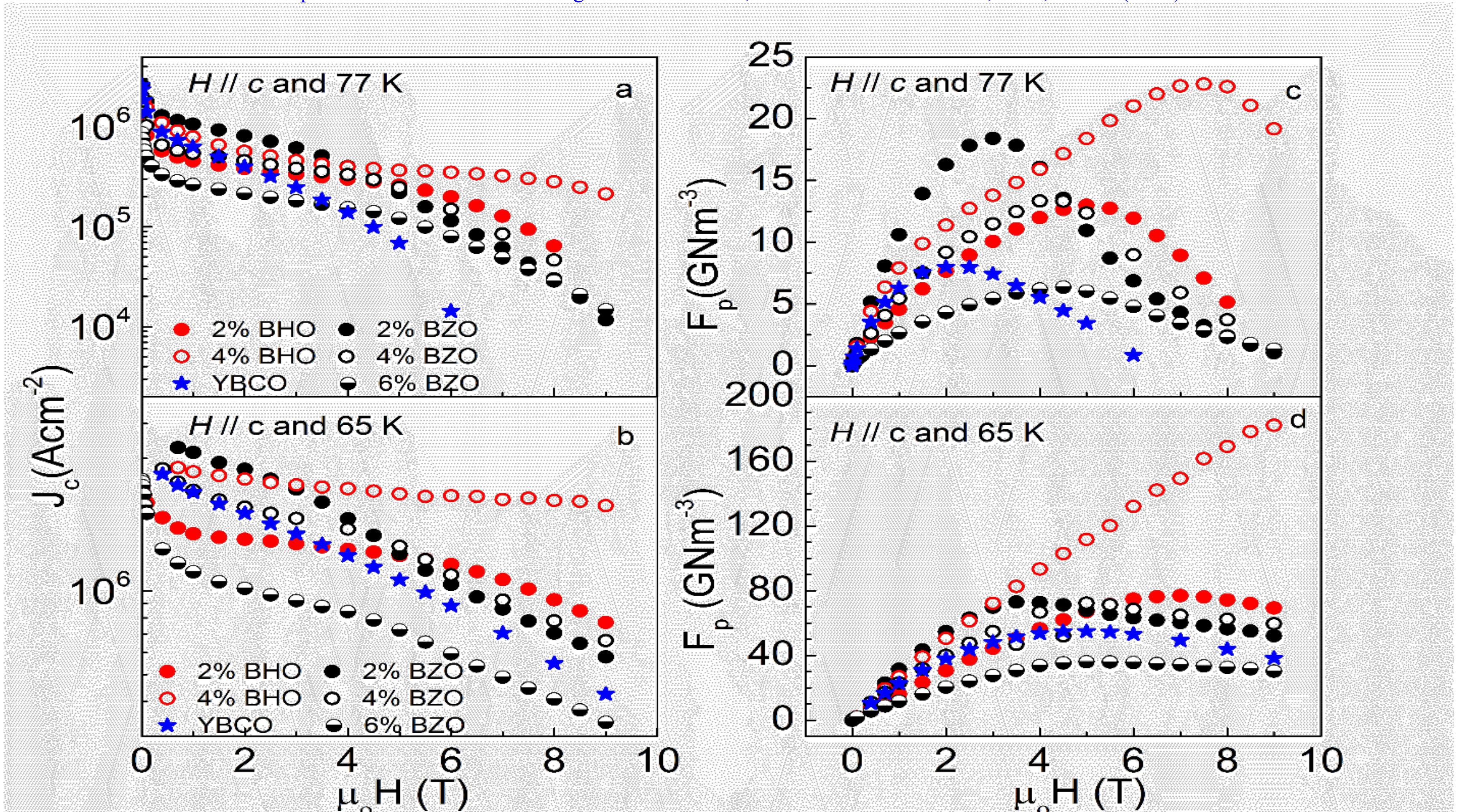
Two co-axial columns around a BZO 1D APC:

- **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.**

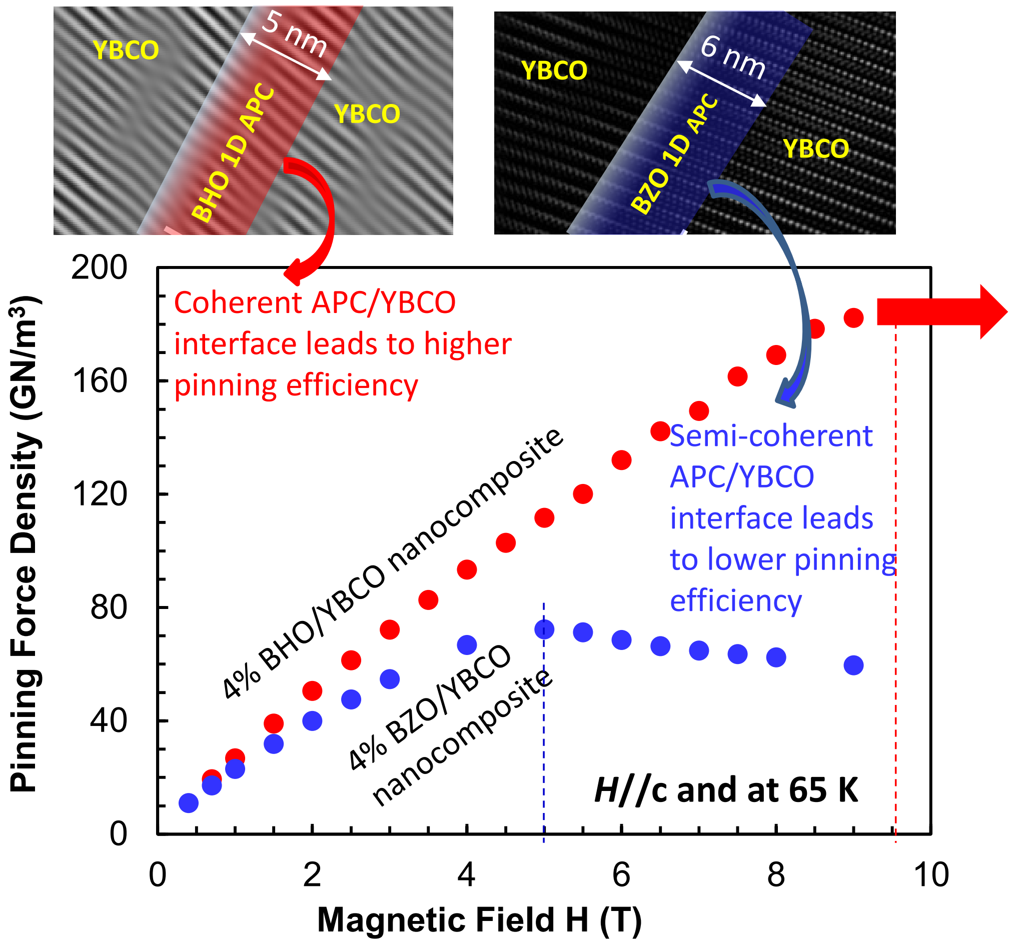




- Semi-coherent BZO 1D APC/YBCO interface
- Coherent BHO 1D APC/YBCO interface is maintained up to 6 vol.% BHO doping



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

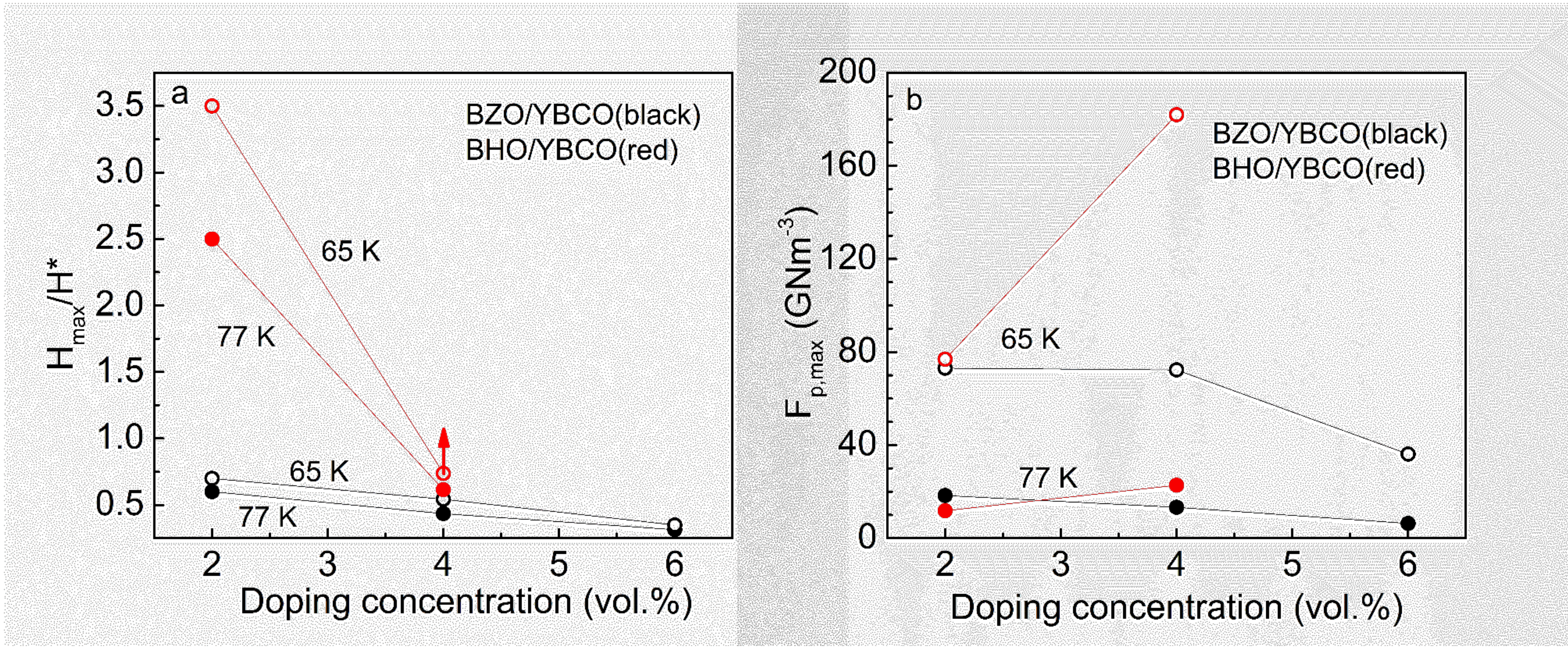


F_p>180 GN/m^3 is the highest so far reported at 65 K.

B. Gautam et al., submitted;
V. Ojigunmi et al., submitted

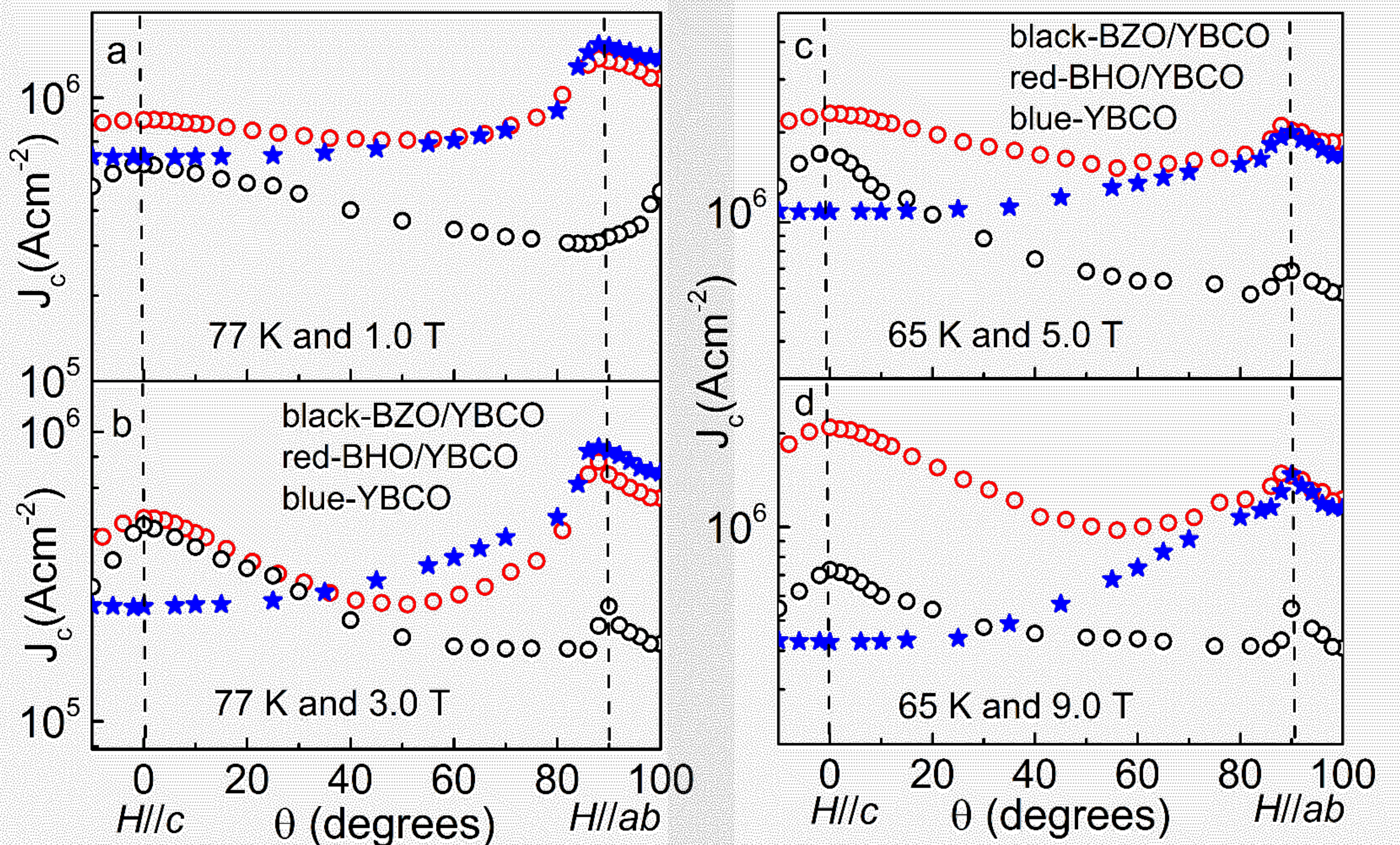
BZO 1D APC: H_{max}~5T (H*~9.2T)
BHO 1D APC: H_{max}>9T (H*~12.2T)

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



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 obtain $F_{p,max}$>180 GN/m^3 and H_{max}/H up to ~3 at 65 K**