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Multilayer BZO/YBCO thick films for high I_c in high fields

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Outline

Effect of strain on APC/REBCO nanocomposites

- Role of strain field in controlling APC morphology, dimension, orientation, etc
- Effect of APC/HTS interface on APC pinning efficiency

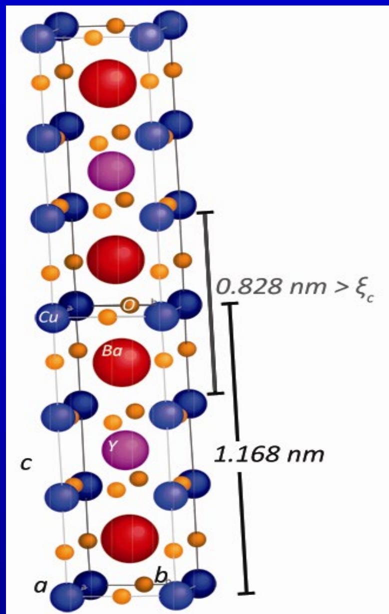
Development of multilayer (ML) approach to dynamically adjust APC/HTS interface strain

- Improving APC/YBCO interface
- Enhancing APC pinning efficiency
- Large Ic in ML films

Summary and future perspectives of APC/HTS nanocomposites for applications

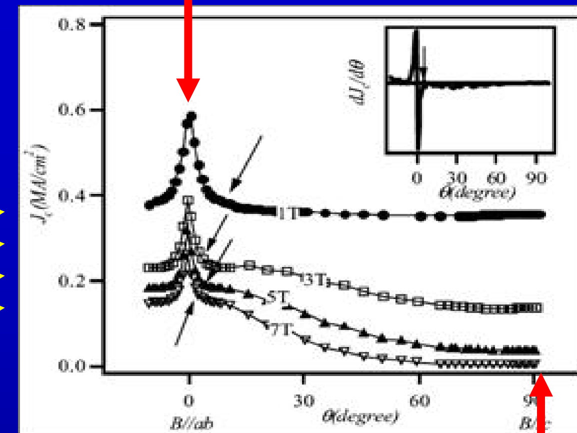
APCs needed in REBCO

c- axis



Layered structure, relatively short ξ_c of YBCO intrinsically provide pinning for H || a-b

ab-plane

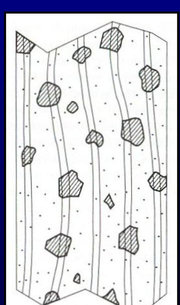


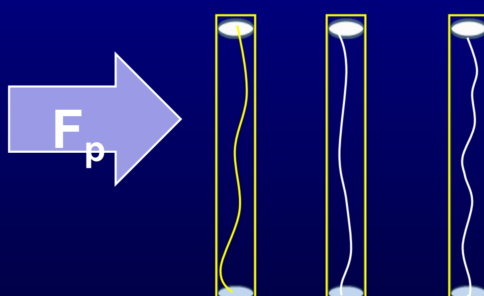
c- axis

With high F_p/L, columnar defects provide a desirable geometry to address weak pinning at H//c-axis

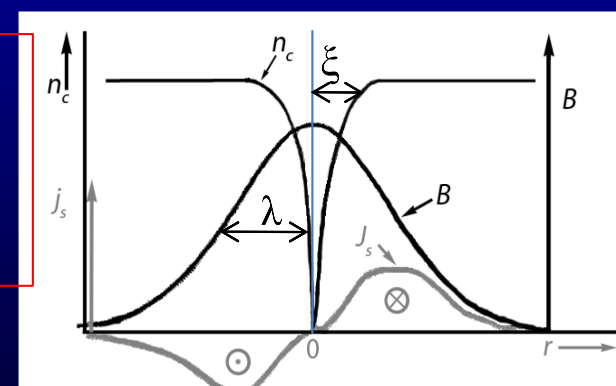
ξ_{ab} ~ a few nm in YBCO determines the APC dimension

$H_{c1} < H < H_{c2}$



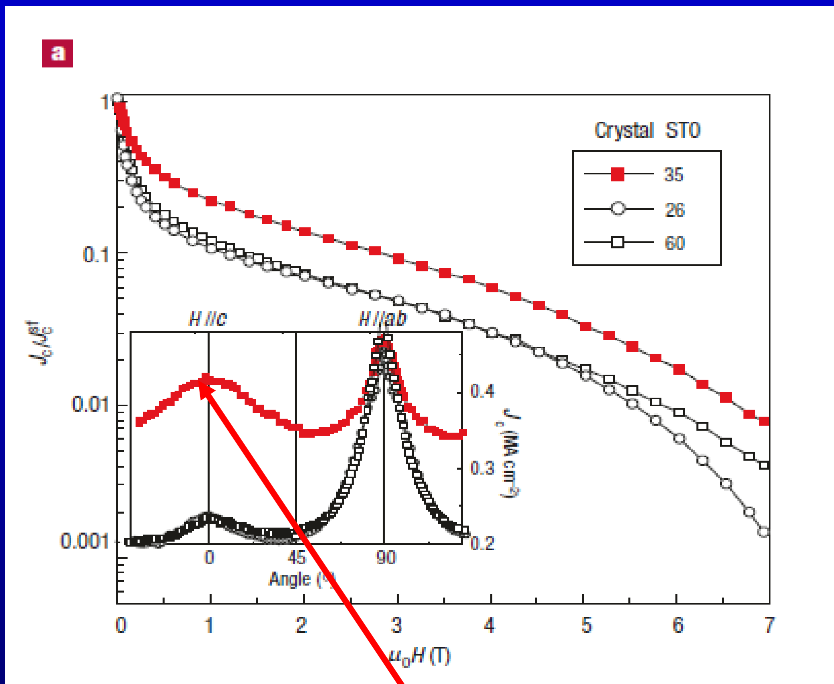


Fp∝ sharpness of the pinning potential energy across the APC/HTS interface



R.P. Huebener, *Magnetic Flux Structures in Superconductors*. Springer (2001); W. Buckel, R. Kleiner, *Superconductivity*, Wiley-VCH, (2004); Blatter G, Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 Vortices in high-temperaturesuperconductors Rev. Mod. Phys. 66 1125

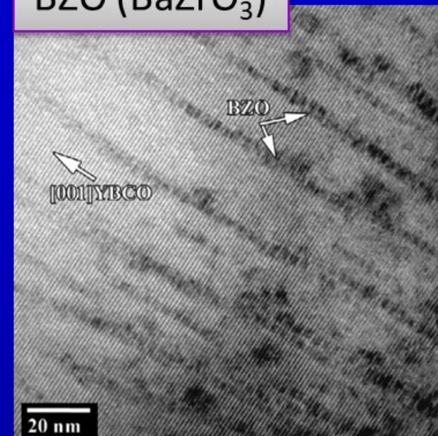
$BaZrO_3$ (BZO) 1D APCs



J. MacManus-Driscoll et al, *Nat. Mat.* **3**, 439 (2004)

Other 1D APCs

BZO ($BaZrO_3$)

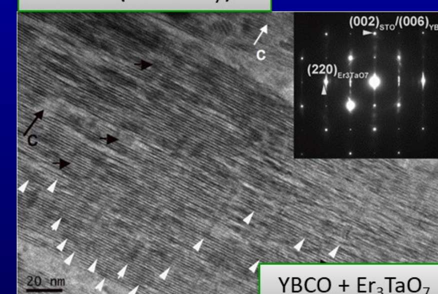


A. Goyal, et al. *Supercond Sci Technol*. **18**, 1553 (2005)

BSO ($BaSnO_3$)

C. V. Varanasi, et al., *Appl Phys Lett* **93**, 092501 (2008).

RTO ($RETaO_7$)

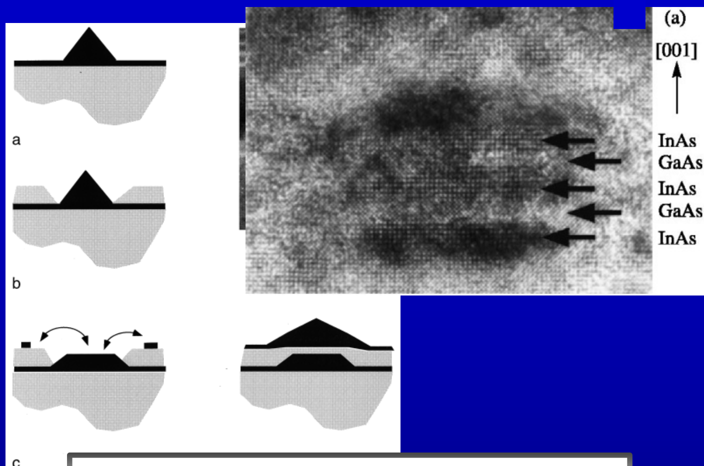


S. A. Harrington, et al. *Supercond Sci Technol*. **22**, 022001 (2009).

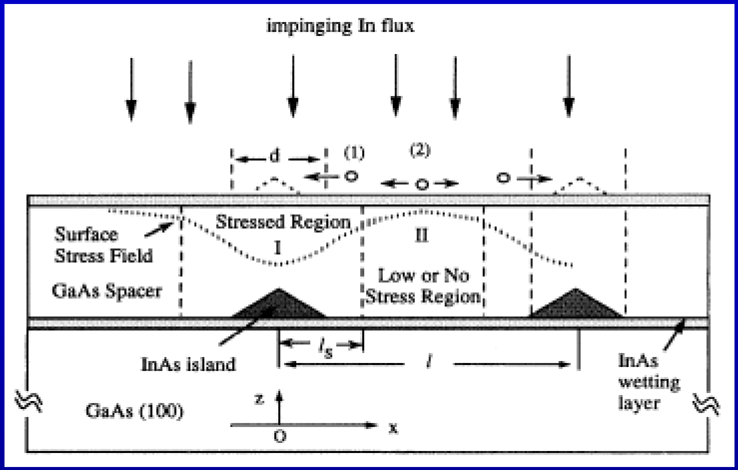
- **C-axis aligned BZO 1D APCs provide strong correlated pining shown as a J_c peak at H//c-axis**
- **Accommodation field $H^{*} \sim n^{*}\Phi_0$ could be estimated from 1D APC areal density n***

Strain Mediated Growth

Strain mediated ordering in semiconducting quantum dots

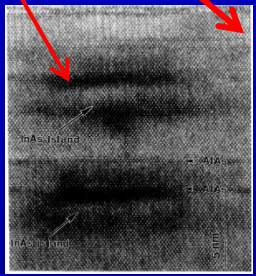


L. Ledentsov, et al. *Phys. Rev. B* **54**, 8743 (1996).



Q. Xie, et al. *Phys. Lett.* **75**, 2542 (1995).

InAs GaAs



$$z_0 = r_0\left(\frac{8L_D}{l}\frac{W}{k_BT}A\right)^{1/3}$$

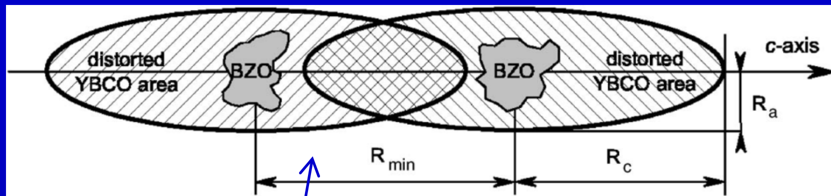
L_D : Diffusion length
r_0 : Island size
W: strain strength
A : Depends on Bulk, Young's moduli

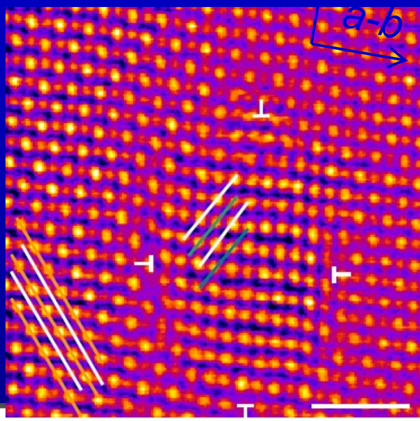
-Preferential growth to minimize strain energy

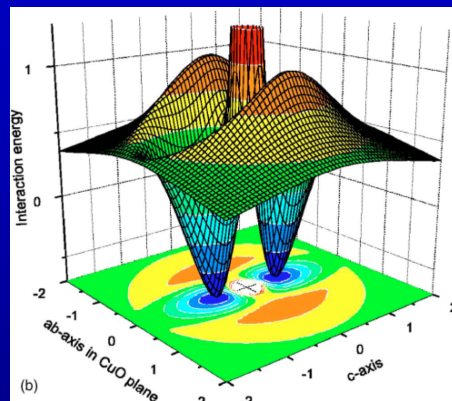
-Dynamically, gradient of strain-mediated surface chemical potential produces diffusion and a driving force for migration of incoming adatoms

-The controlling strain is from the mismatch between matrix and QDs.

APC Formation – Interfacial strain mediated growth

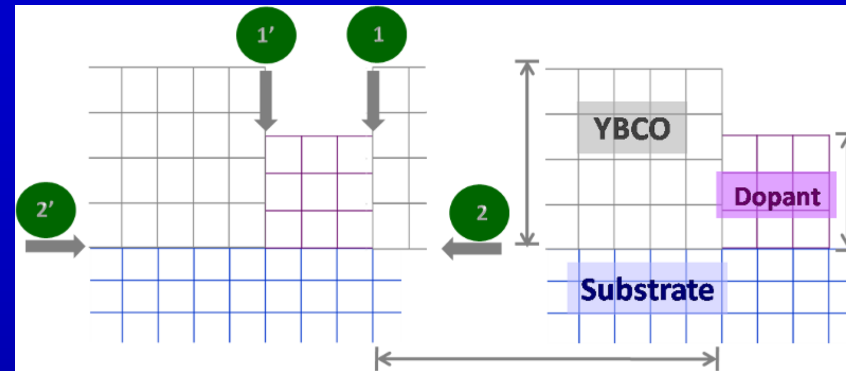






S. Kang, et al. *Supercond Sci Technol*. **18**, 1553 (2005).

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

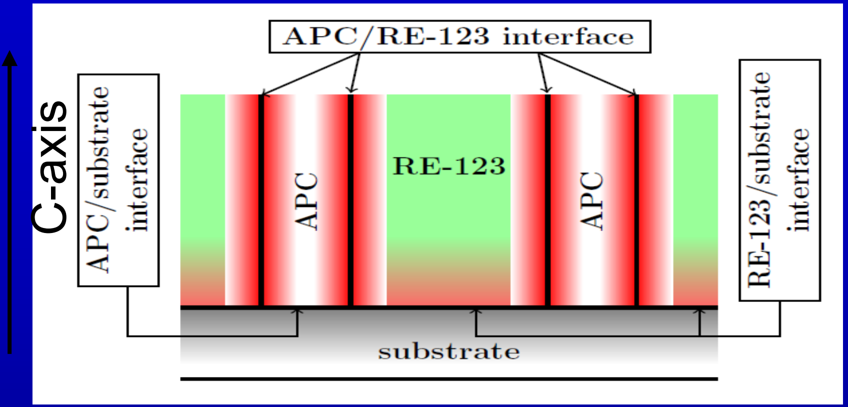


Misfit to *YBCO* $(a_1 - a_2 / a_2)$	*[100]*	*[010]*	*[003]*
BZO (PDF #03-0632)	**8.85%**	**7.25%**	**7.08%**
BSO (PDF #15-0780)	**7.22%**	**5.59%**	**5.42%**

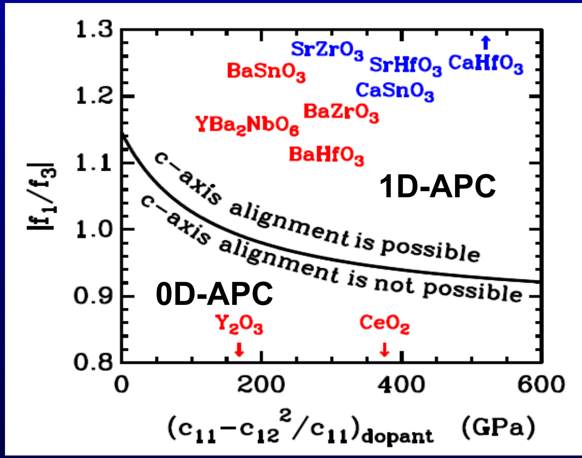
- Similar alignment mechanism
- The controlling strain is from the mismatch between the YBCO and BZO and is anisotropic—BZO cylinder shape and aligned
- *YBCO matrix is under tensile strain—lower T_c, low-field J_c, high resistivity*

Strain field initiated from 1D APC/RE-123 interface plays a critical role in self-assembly of the 1D-APCs

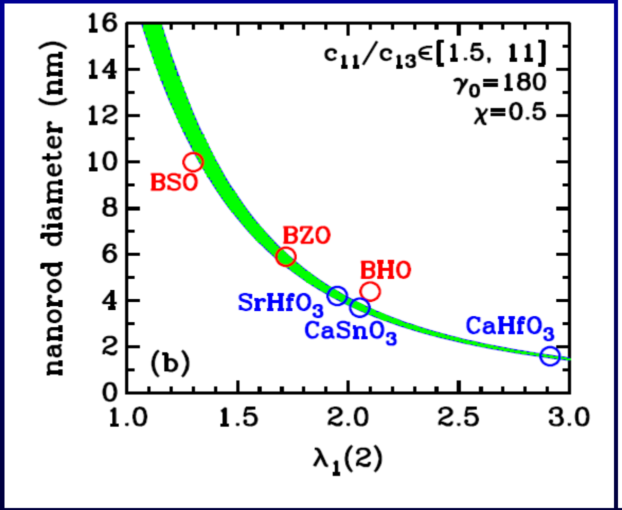
Elastic strain energy model



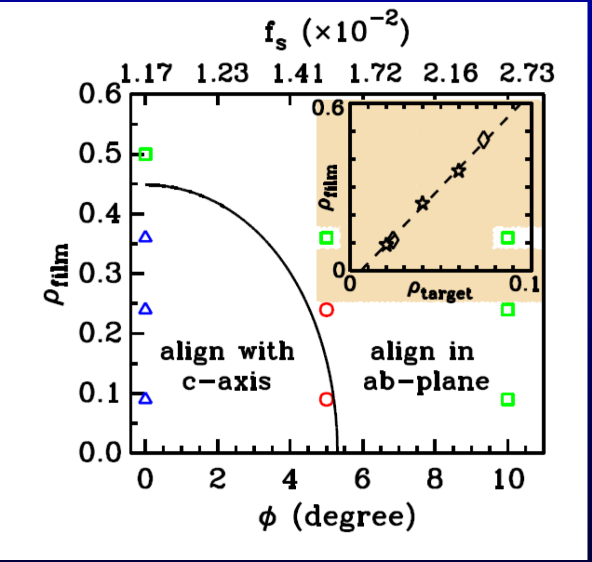
APC material selection



APC dimension



Mixed 1D+2D+3DAPCs

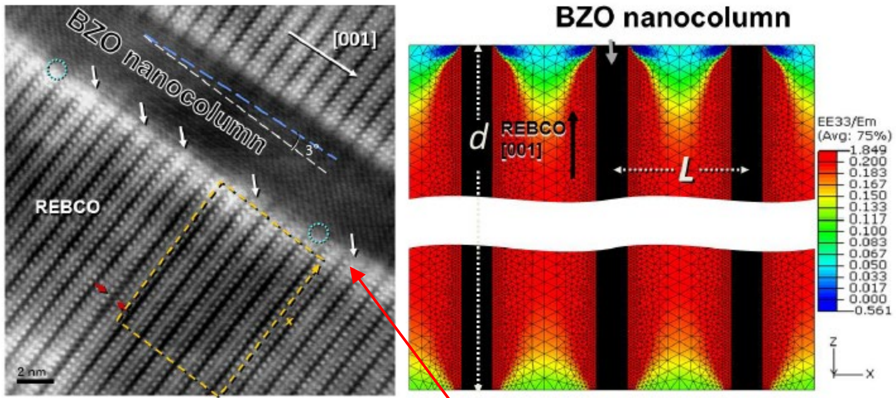


- Shi and Wu, *Philosophic Magazine* **92**, 2911 (2012); ***92**, 4205* (2012);
- Wu and Shi, SUST 30, 103002 (2017) in SUST Special Issue on Artificial Pinning Centers
- Wu, Gautam and Ogunjimi, in *Superconductivity*, ed. by Kosmas Prassides, Chiara Tarantini, Anna Palau, Petre Badica, Alok K Jha, Tamio Endo and Paulo Mele, Springer (2020). Page 29-52.

The bad news of the strain field

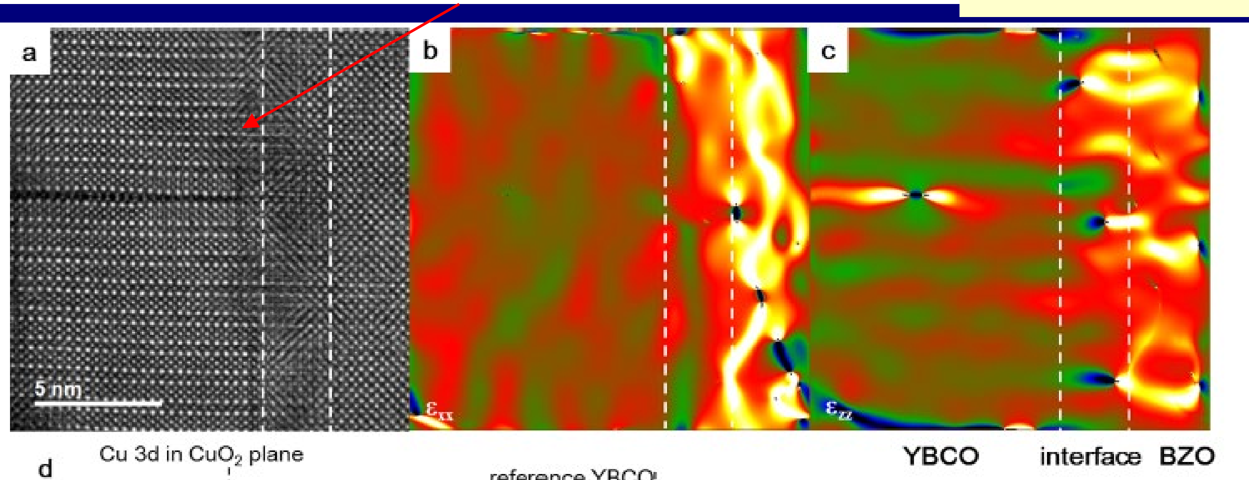
Strain field initiated from 1D APC/RE-123 interface due to a large BZO/YBCO lattice mismatch of ~ 7.7%

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



BZO 1D-APC/YBCO interface is defective

- **A defective, oxygen-deficient YBCO column around the BZO/YBCO interface**
- **This raises a question on the impact on the pinning efficiency of BZO 1D-APCs**



T. Horide et al. *ACS Nano* **11**, 1780 (2017).

Strain field is a double-edge sword in APC/HTS nanocomposites

Good: It plays a critical role in strain-mediated APC growth and determines morphology, dimension, concentration, orientation, etc

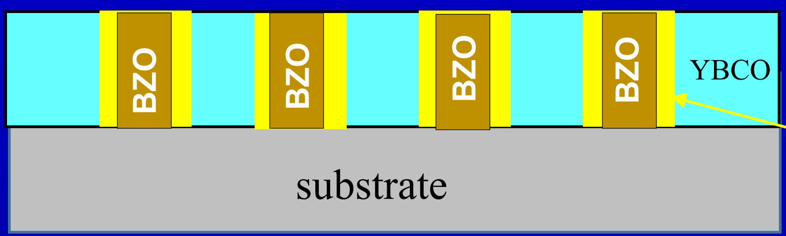
Bad: It may lead to defective APC/HTS interface that could reduce the pinning efficiency of APCs

(1) $B_{max}<B^*$ -- a substantial number of 1D APCs generated are not contributing to pinning

(2) low F_p since it is proportional to the sharpness of the APC/HTS interface

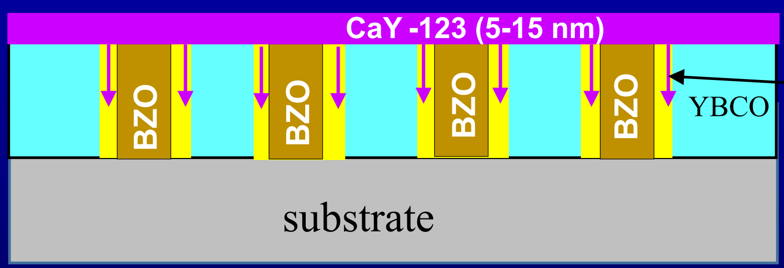
Multilayer approach: dynamic control of the BZO/YBCO interface

Step 1: deposition of BZO/YBCO



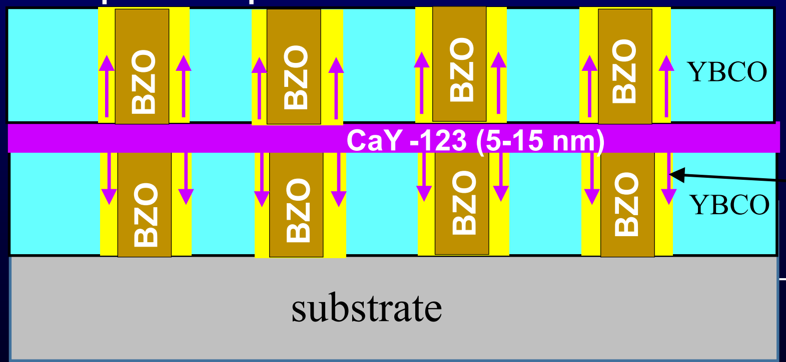
- BZO 1D-APCs form similarly to the case single-layer BZO/YBCO nanocomposite films
- Tensile strained BZO/YBCO interface due to 7.7% lattice mismatch

Step 2: deposition of $Ca_{0.3}Y_{0.7}Ba_2Cu_3O_7$



Cu substitution by 30% larger Ca ions favored energetically by the tensile strained BZO/YBCO interface, leading to enlarged YBCO c-axis and reduced lattice mismatch at the BZO/YBCO interface

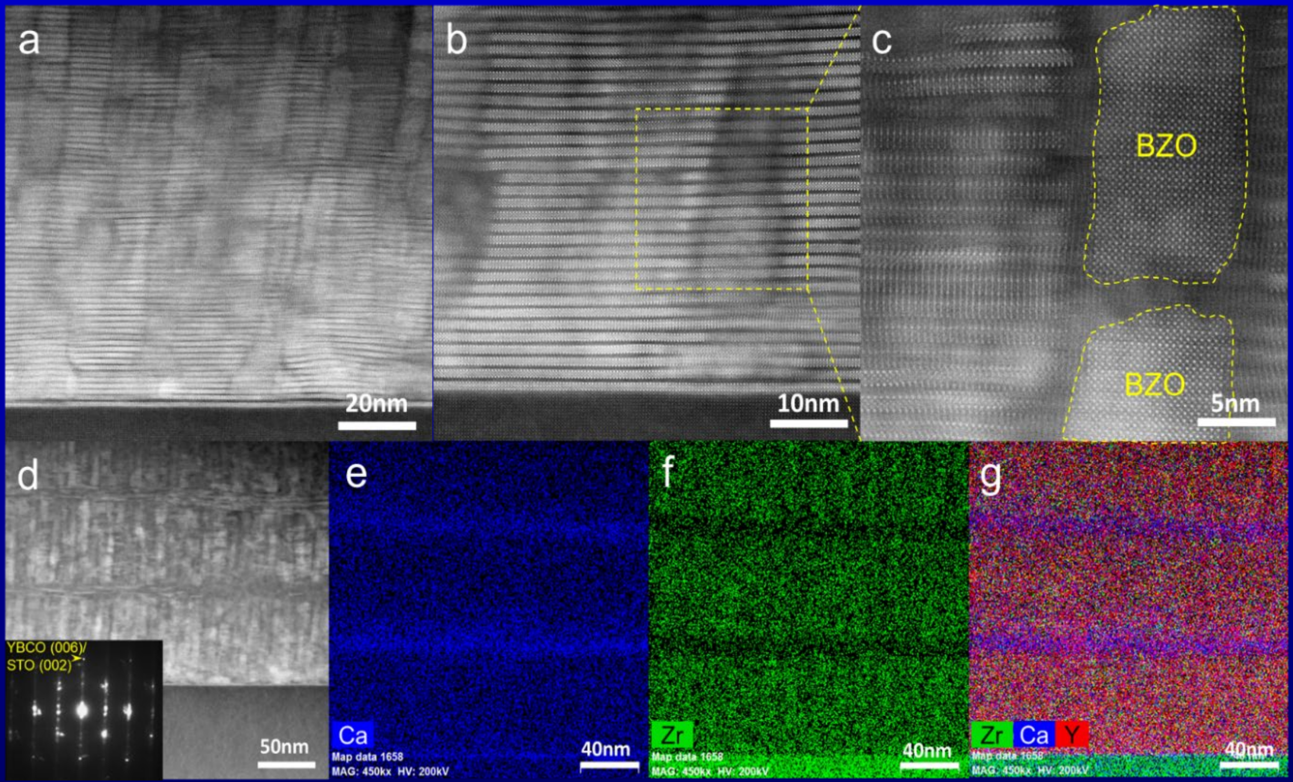
Step 3: deposition of BZO/YBCO



- 2-8% of BZO/YBCO with layer thickness of 50-250 nm tested for Ca diffusion
- The ML deposition can be repeated for thick films

Ogunjimi et al, SUST 34, 104002 (2021); Wu, et al, SUST **35**, 034001 (2022)

STEM/EDS characterization

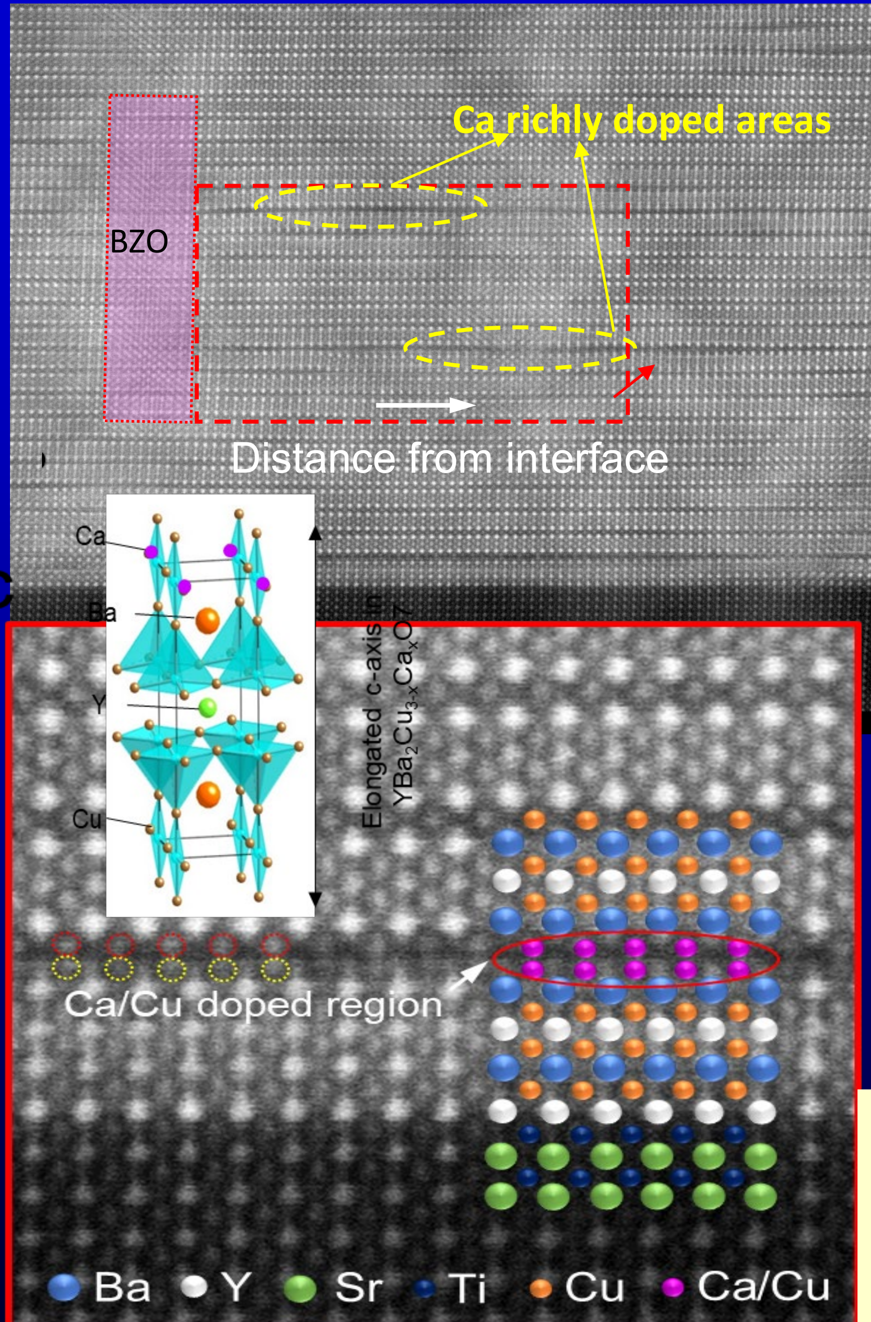


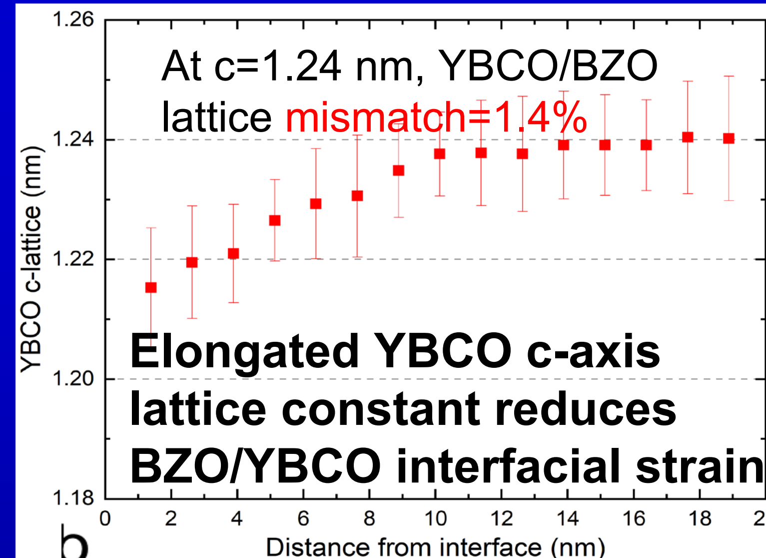
6% BZO/YBCO single-layer (SL) nanocomposite film

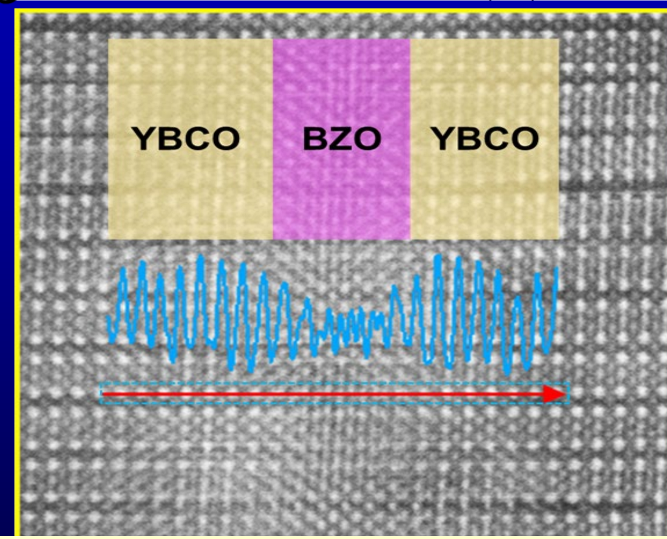
6% BZO/YBCO multilayer (ML) nanocomposite film

Ogunjimi et al, SUST 34, 104002 (2021); Wu, et al, SUST **35**, 034001 (2022)

- **BZO 1D-APCs have comparable diameters and areal concentrations in SL and ML samples**
- **Minor Ca diffusion from CaY-123 spacers to YBCO during PLD growth is clearly visible from STEM/EDS elemental maps**



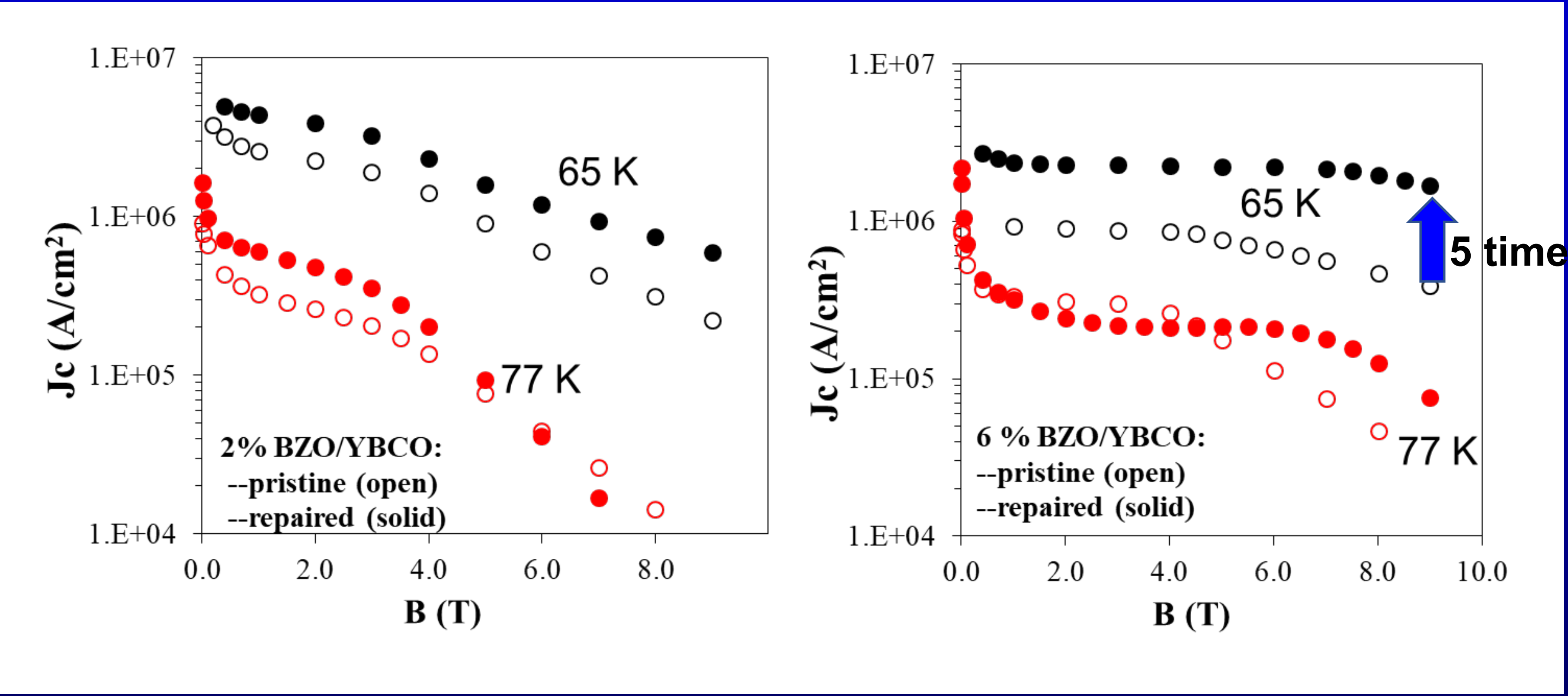




Ca/Cu replacement on YBCO's Cu-O planes causes the c-lattice elongation and prevents formation of defects on BZO/YBCO interface

2% BZO/YBCO
T_c~88.5 K (SL or pristine))
T_c~87.5 K (ML or repaired)

6% BZO/YBCO
T_c~86.9 K (SL or pristine)
T_c~84.5 K (ML or repaired)



- **Despite slightly lower T_c values, enhanced J_c (B) was observed in ML samples with a coherent BZO/YBCO interface**
- **At 65 K, J_c is enhanced over the entire B field range up to 9.0 T**

Ogunjimi et al, SUST 34, 104002 (2021); Wu, et al, SUST **35**, 034001 (2022): Wu at al, IEEE Trans. Appl. Supercond. (2023)

2% BZO/YBCO
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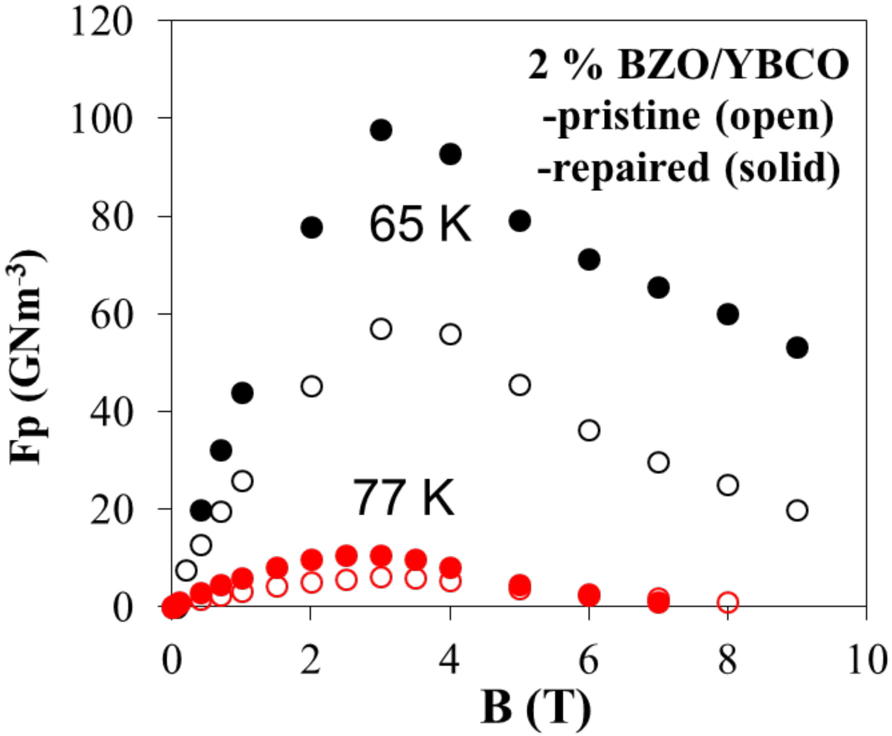
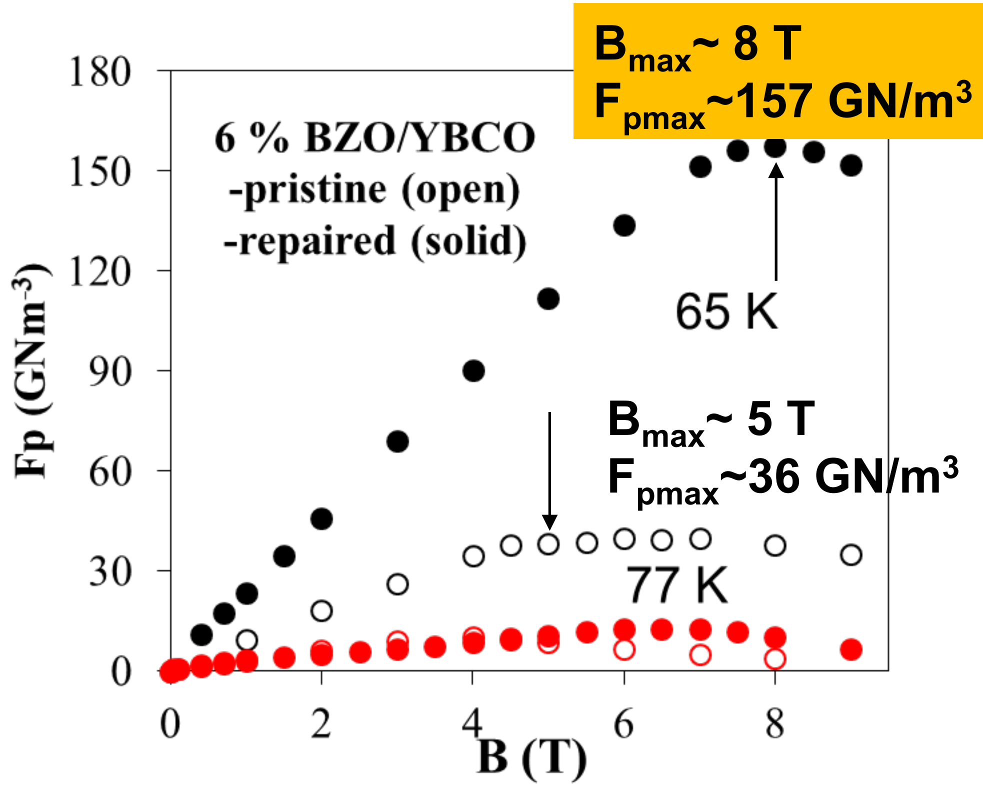
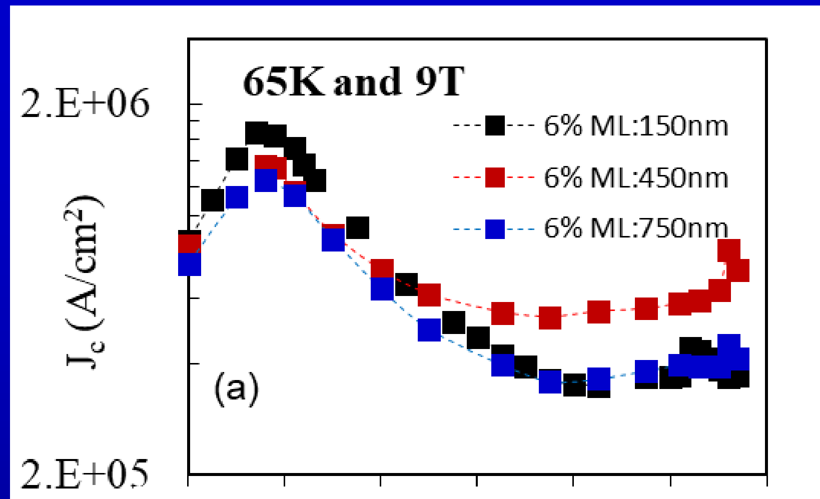


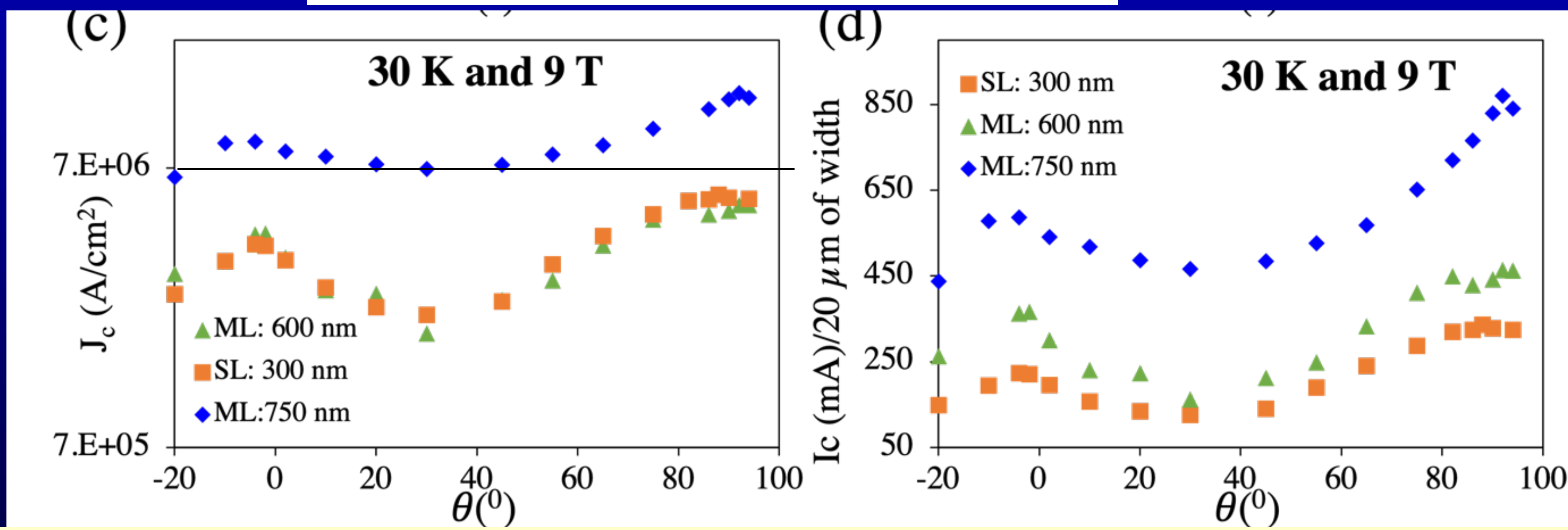


- **At 65 K, the peak F_{pmax}~157 GN/m^3 in 6% ML BZO/YBCO is 4.4 times of that in the SL 6% BZO/YBCO sample**
- **B_{max} is increased by 60% to 8.0 T in 6% ML BZO/YBCO, but there is still a room for further improvement considering B* ~ 9.2 T**

Thick ML films at low temperatures



Panth et al, submitted



- **At 65 K, 6% BZO/YBCO ML samples with thickness of 150-750 nm have comparable Jc values.**
- **At low temperature, 750 nm thick ML film outperforms thinner counterparts**

Future perspectives: emphasize practical needs

- Exciting progress has been made in research and development of APCs, particularly through a transition from empirical try-and-error to APC-landscape-by-design
- The future research on APC/REBCO nanocomposites needs to consider other application requirements such as:

❑ mechanical strength,

❑ radiation sustainability,

❑ Throughputs and cost