Ca-repaired $BaZrO_3$ nanorods/$YBa_2Cu_3O_{7-x}$ interface for enhanced pinning in $YBa_2Cu_3O_{7-x}$ nanocomposites with 2-8% $BaZrO_3$ doping

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Outline

Effect of strain on APC/REBCO nanocomposites

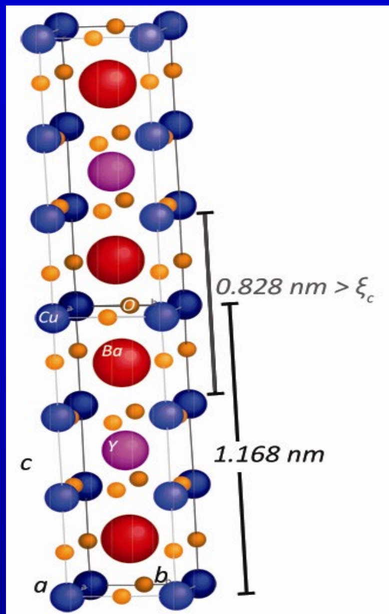
- Role of strain field in controlling APC morphology, dimension, orientation, etc
- Effect of APC/HTS interface on APC pinning efficiency

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

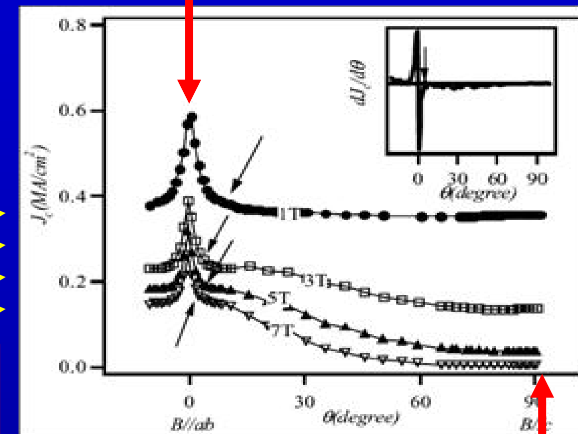
APCs needed in REBCO



c- axis

Layered structure, relatively short ξ_c of YBCO intrinsically provide pinning for $H \parallel a\text{-}b$

ab-plane

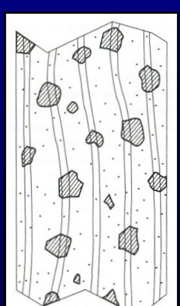


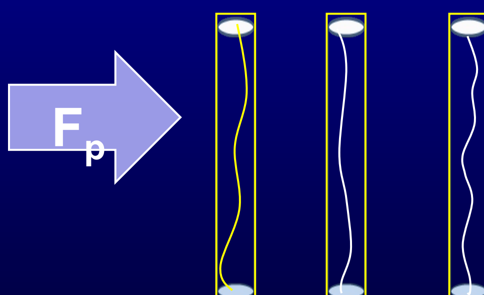
c- axis

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

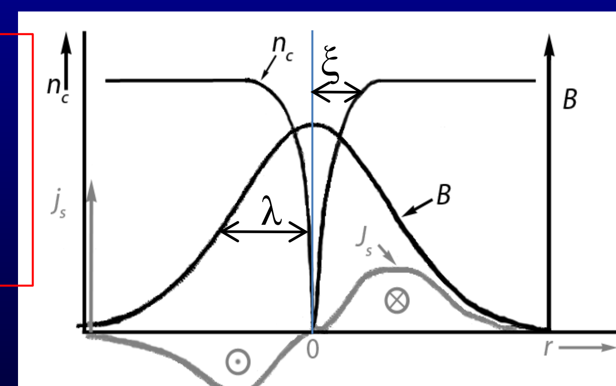
ξ_{ab} ~ a few nm in YBCO determines the APC dimension

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



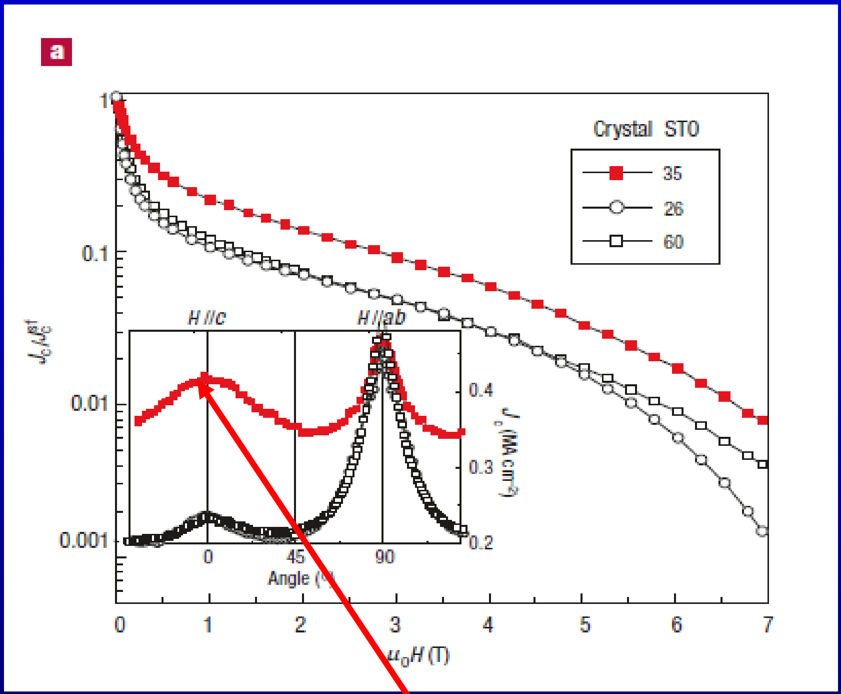


Fp∝ sharpness of the pinning potential energy across the APC/HTS interface



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

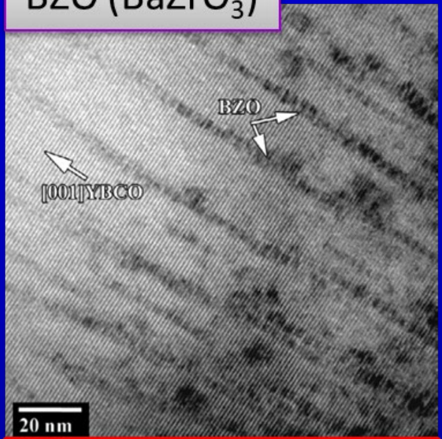
$BaZrO_3$ (BZO) 1D APCs



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

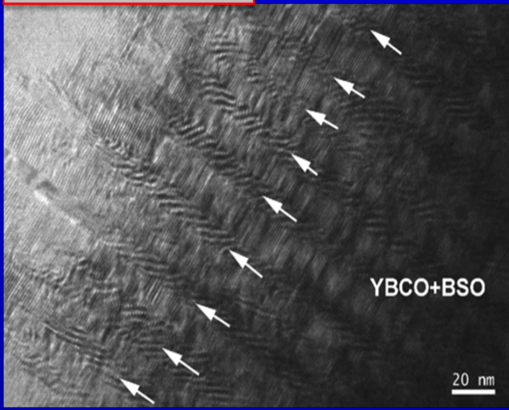
Other 1D APCs

BZO ($BaZrO_3$)



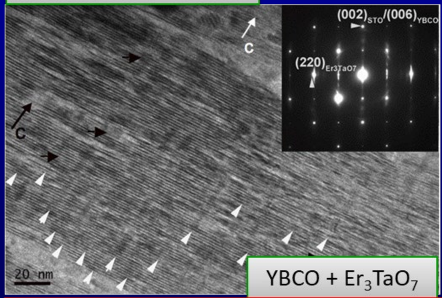
A. Goyal, et al. *Supercond Sci Technol*. **18**, 1553 (2005)

BSO ($BaSnO_3$)



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

RTO ($RETaO_7$)



YBCO + Er_3TaO_7

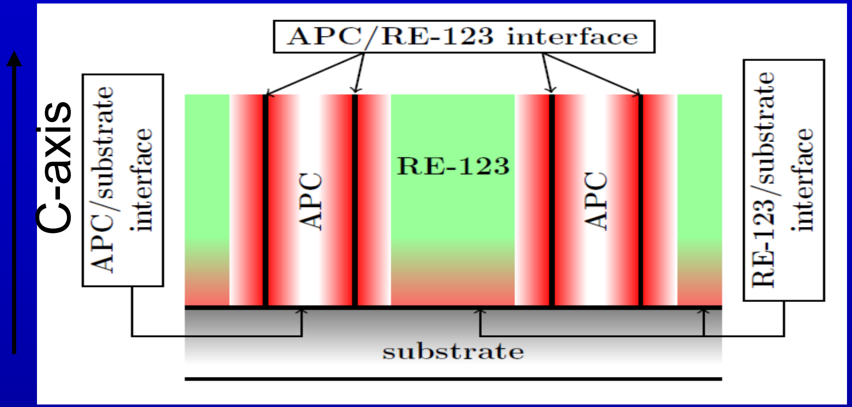
S. A. Harrington, et al. *Supercond Sci Technol*. **22**, 022001 (2009).

- **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***

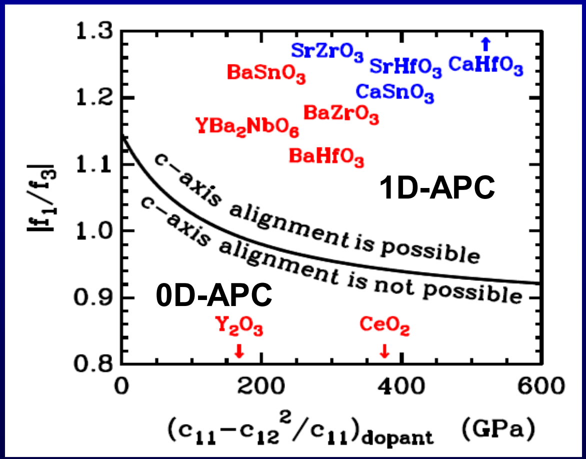
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition)
October, 2023. Presentation given at CEC-ICMC, July, 2023, Honolulu, Hawaii, USA

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

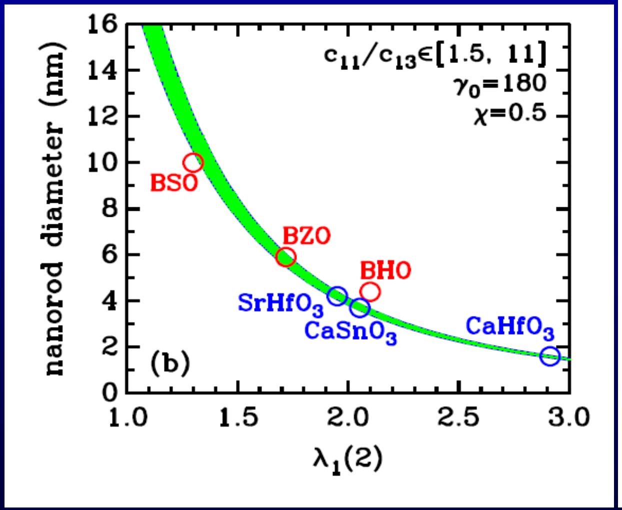
Elastic strain energy model



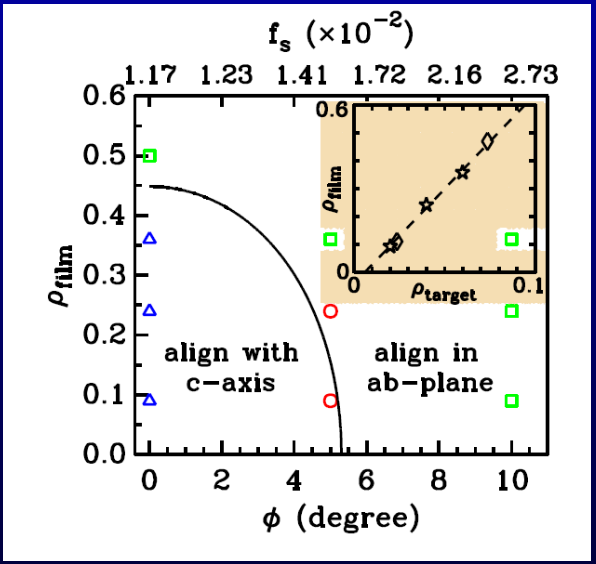
APC material selection



APC dimension



Mixed 1D+2D+3DAPCs

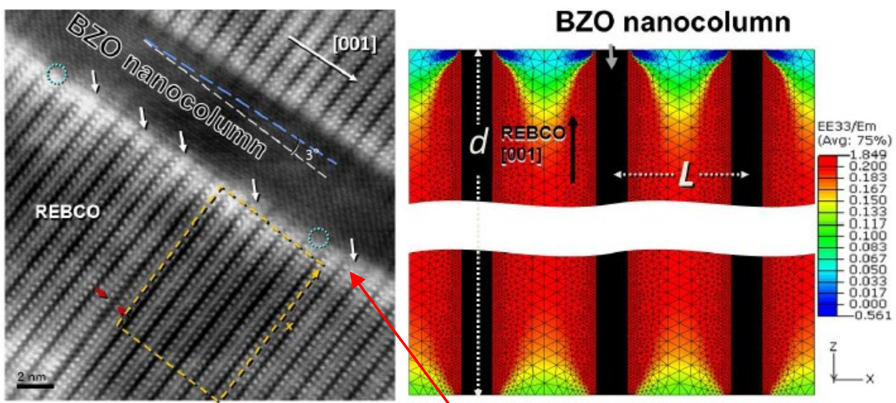


- Shi and Wu, *Philosophic Magazine* **92**, 2911 (2012); ***92**, 4205* (2012);
- Wu and Shi, SUST 30, 103002 (2017) in SUST Special Issue on Artificial Pinning Centers
- Wu, Gautam and Ogunjimi, in *Superconductivity*, ed. by Kosmas Prassides, Chiara Tarantini, Anna Palau, Petre Badica, Alok K Jha,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

The bad news of the strain field

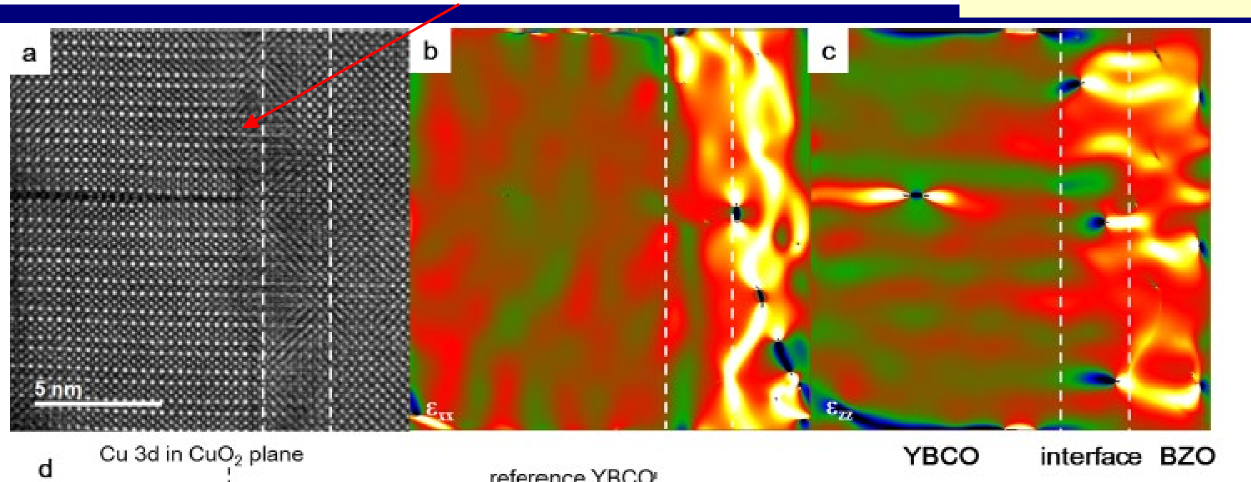
Strain field initiated from 1D APC/RE-123 interface due to a large BZO/YBCO lattice mismatch of ~ 7.7%

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



BZO 1D-APC/YBCO interface is defective

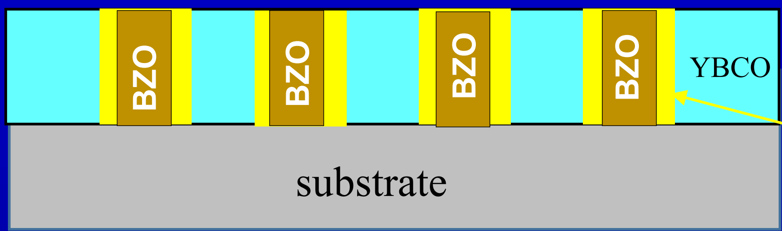
- **A defective, oxygen-deficient YBCO column around the BZO/YBCO interface**
- **This raises a question on the impact on the pinning efficiency of BZO 1D-APCs**



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

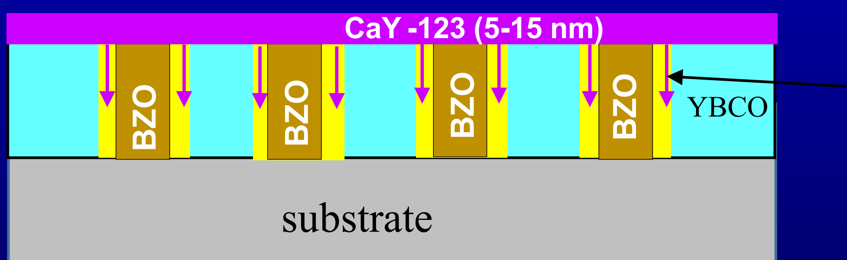
Multilayer approach: dynamic control of the BZO/YBCO interface

Step 1: deposition of BZO/YBCO



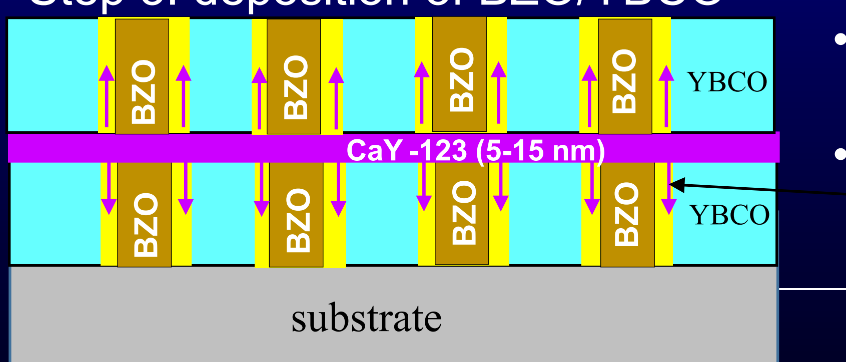
- BZO 1D-APCs form similarly to the case single-layer BZO/YBCO nanocomposite films
- Tensile strained BZO/YBCO interface due to 7.7% lattice mismatch

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

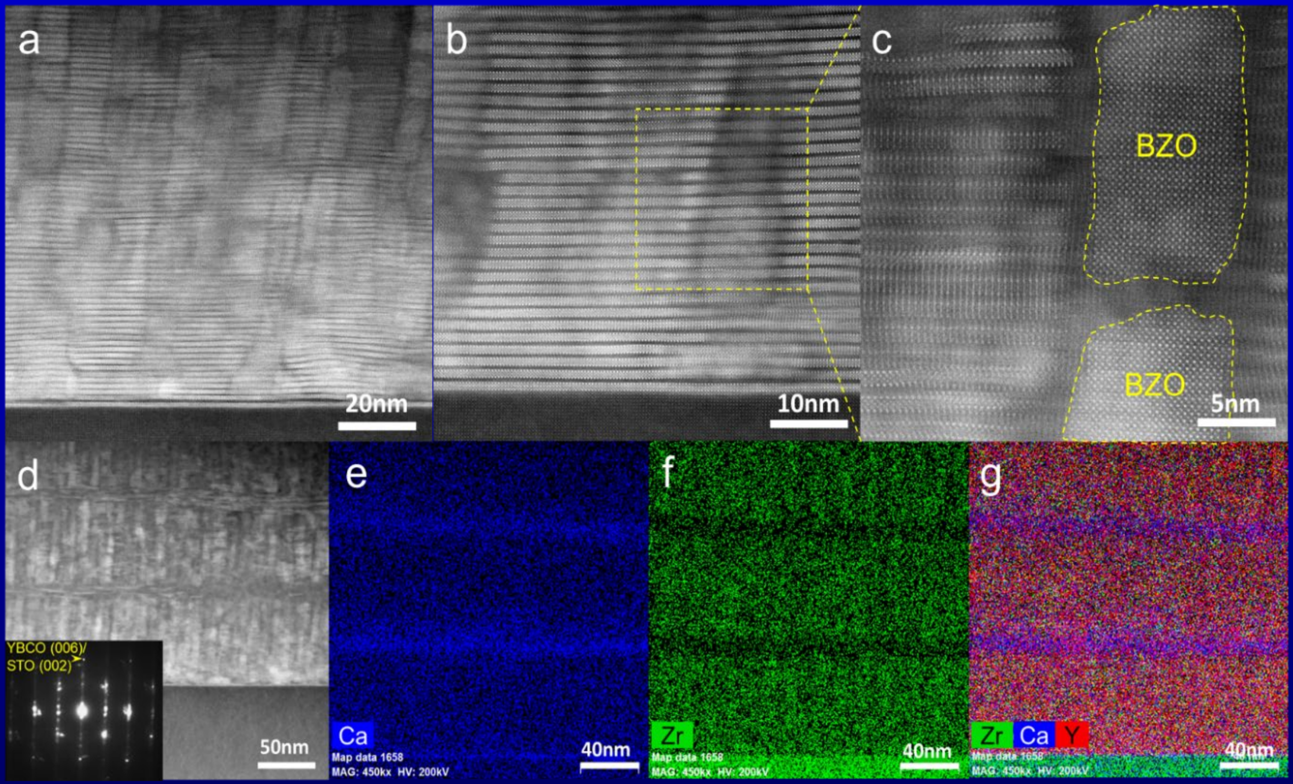
Step 3: deposition of BZO/YBCO



- 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

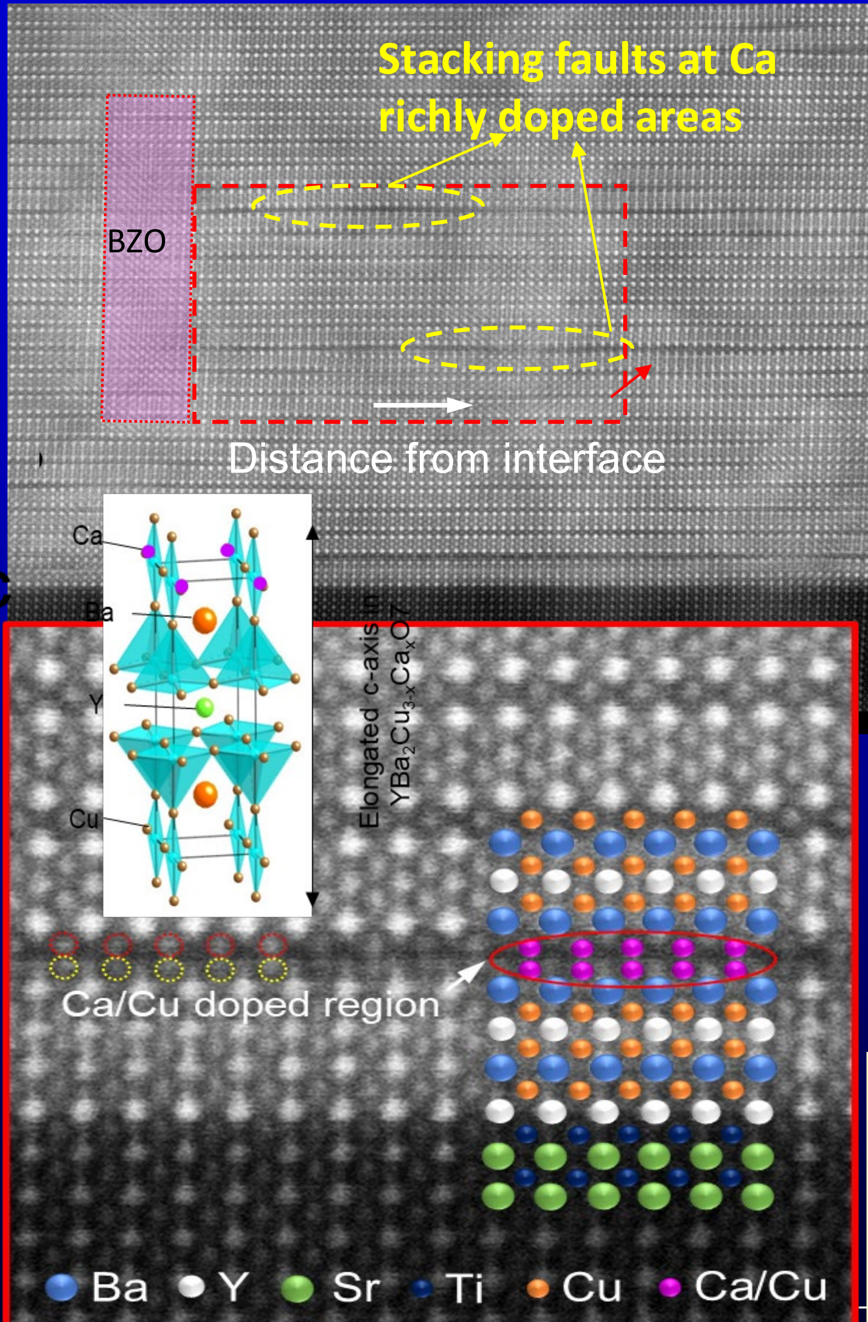


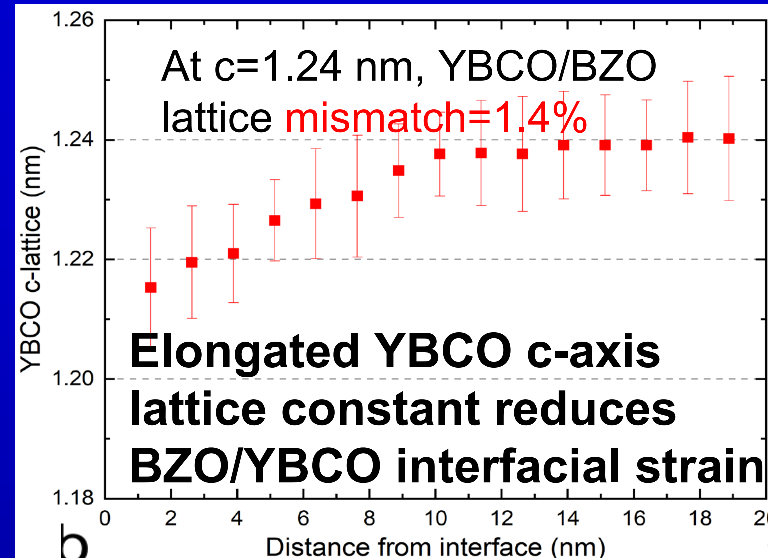
6% BZO/YBCO single-layer (SL) nanocomposite film

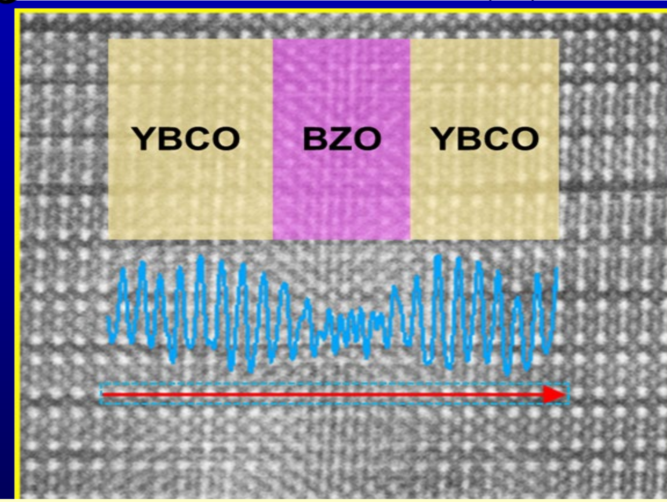
6% BZO/YBCO multilayer (ML) nanocomposite film

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**

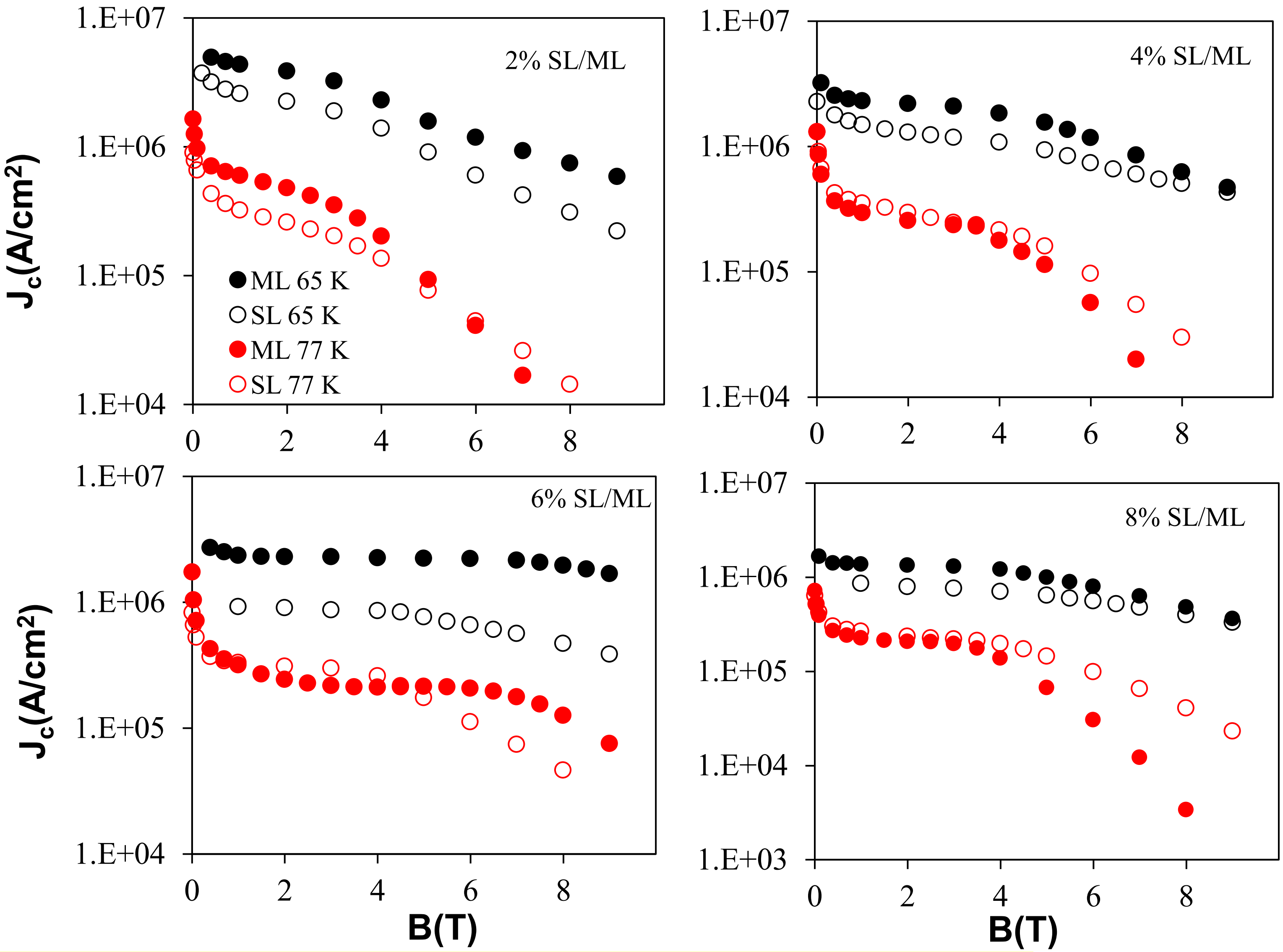






Ca/Cu replacement on YBCO's Cu-O planes leads to stacking faults formation and hence the c-lattice elongation, which prevents formation of defects on BZO/YBCO interface

J_c in 2-8% BZO/YBCO ML and SL films

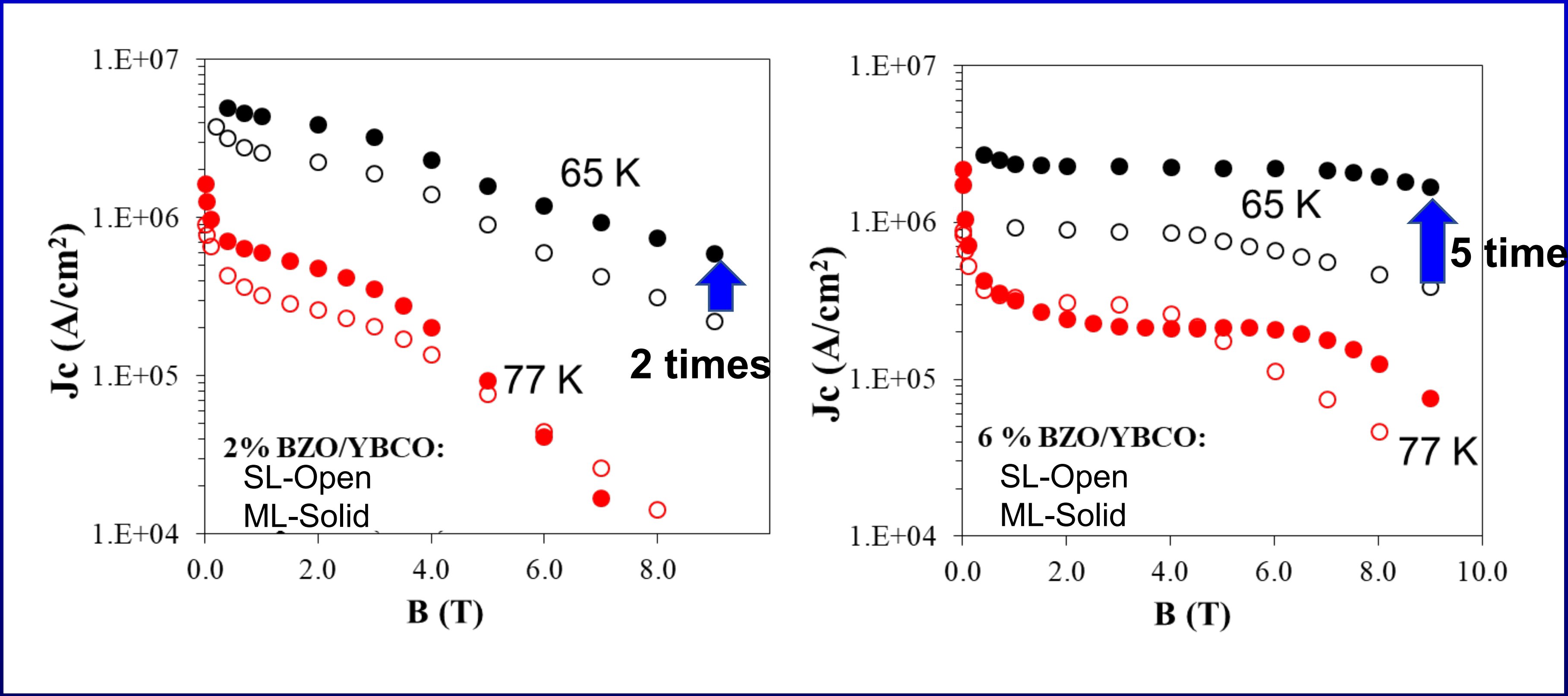


Improved J_c has been observed in all ML films doped with 2-8% BZO doping

Panth at al, IEEE Trans. Appl. Supercond. **32** P1-8 (2022)

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

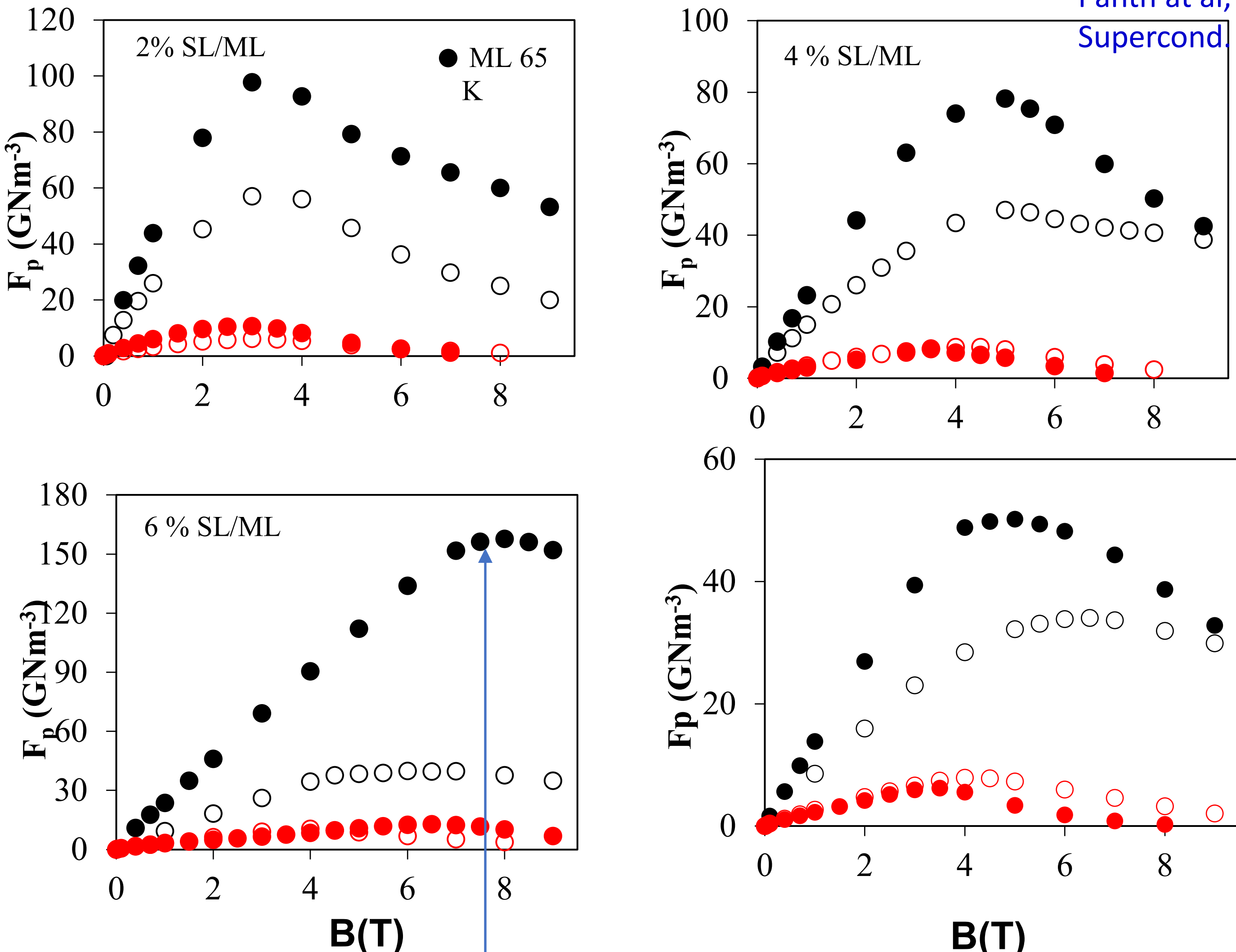
6% BZO/YBCO
T_c~86.9 K (SL)
T_c~84.5 K (ML)



- **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**

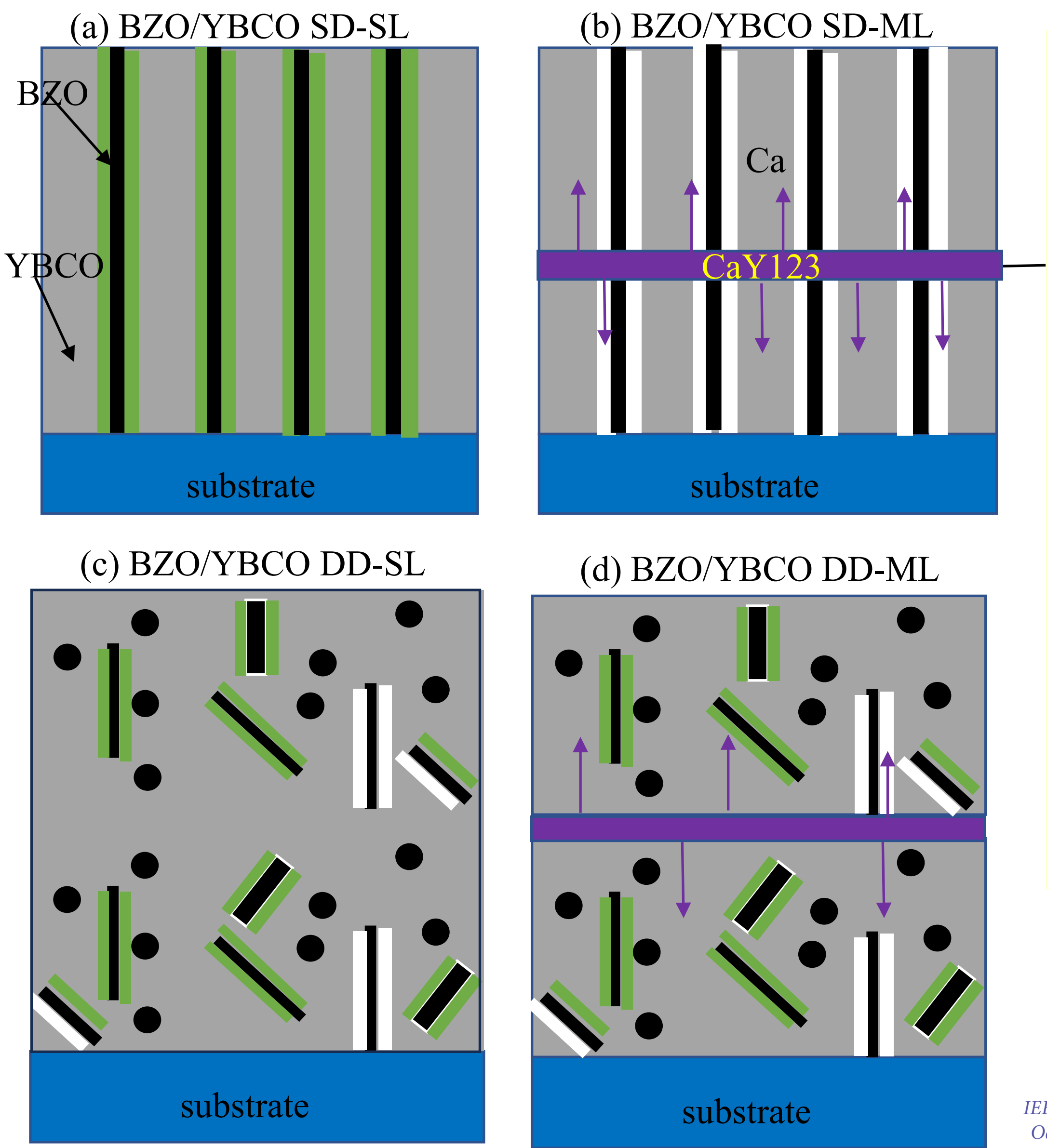
Ogunjimi et al, SUST 34, 104002 (2021); Wu, et al, SUST **35**, 034001 (2022): Wu at al, IEEE Trans. Appl. Supercond. (2023)

Panth at al, IEEE Trans. Appl. Supercond. **32** P1-8 (2022)



- 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

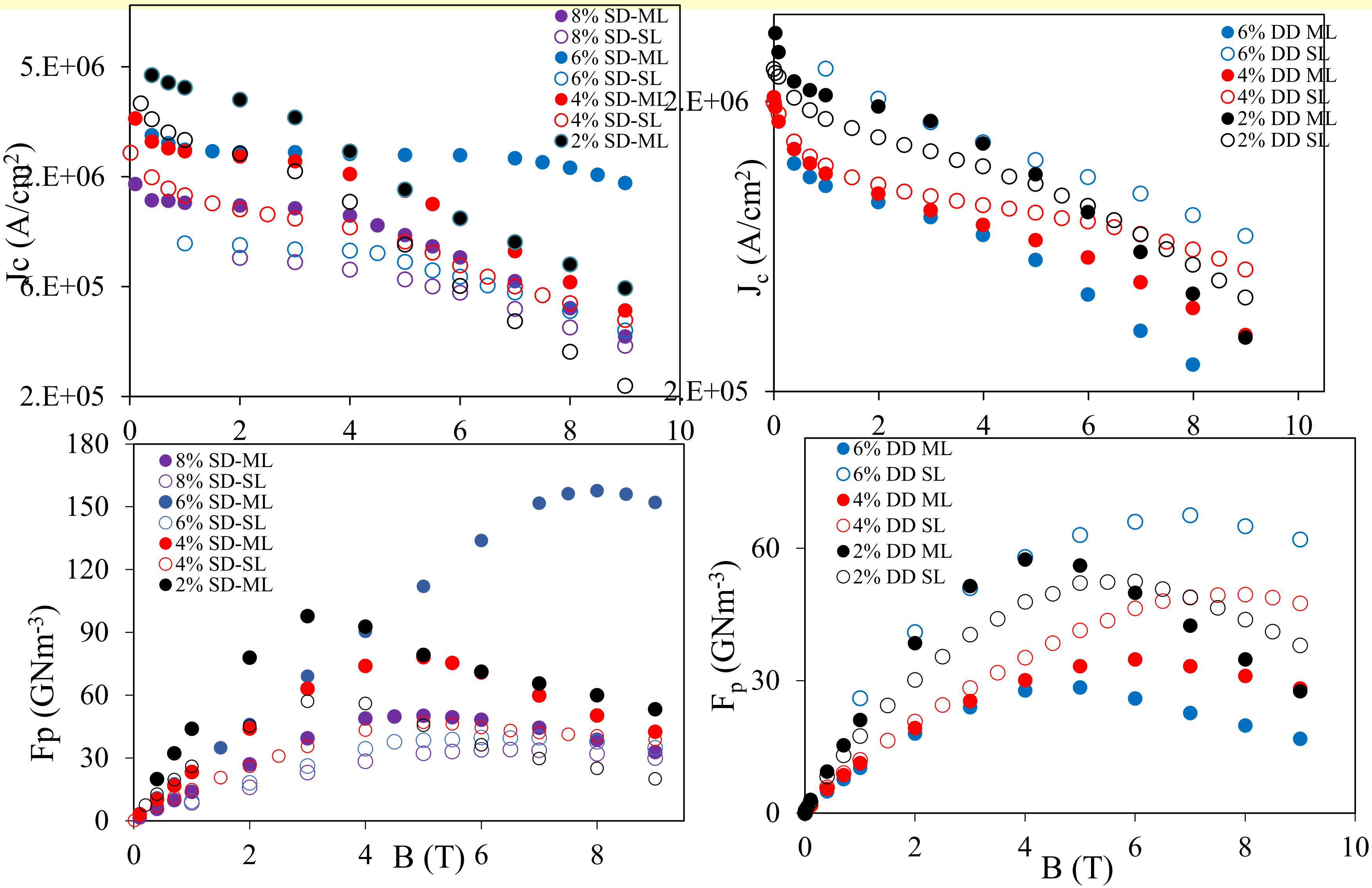
Effect of strain field on the Ca ion diffusion in $BaZrO_3$-Y_2O_3 doped $YBa_2Cu_3O_{7-x}$/$Ca_{0.3}Y_{0.7}Ba_2Cu_3O_{7-x}$ multilayer nanocomposite films



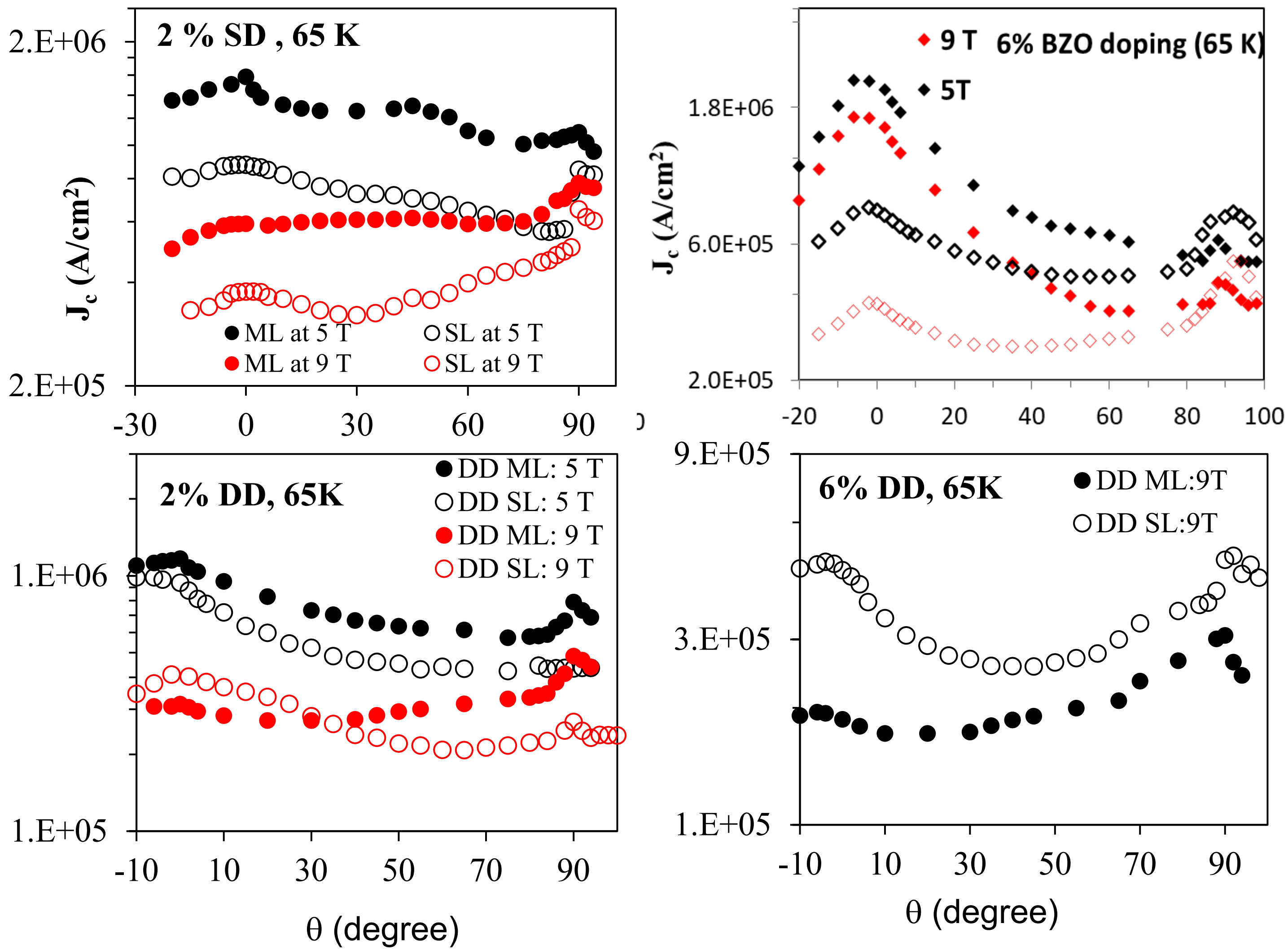
- **The tensile strain at the BZO/YBCO interface makes Ca-diffusion along the interface and Ca/Cu substitution energetically favorable**
- **In DD ML samples with >4% BZO, BZO 1D-APCs become segmented with random orientations, which releases the modulated BZO/YBCO interfacial strain and changes the Ca-diffusion**

Panth at al, IOP MRX **10** P046001 (2023)

Improved pinning only observed on 2%$BaZrO_3$-Y_2O_3 double-doped ML films, confirming the effect of strain on Ca-difusión and APC pinning



Panth at al, IOP MRX **10** P046001 (2023)



Enhanced pinning efficiency of the BZO 1D APCs in BZO/YBCO ML samples also extends to a broad angular range up to 85 degree with respect to the B orientations especially at high B fields

Summary

- **Using a ML method, a coherent BZO 1D APC/YBCO interface can be obtained through Ca/Cu replacement induced stacking faults that leads to reduction of the BZO/YBCO lattice mismatch from 7.7% to 1.4% and prevents defects formation at the BZO/YBCO interface**
- **Coherent 1D APC/RE-123 interface is the key to achieve high pinning efficiency of 1D-APCs including high F_p(H), B_{max}/B^*, and isotropic $J_c(\theta)$ in high B fields**
- **Significantly enhanced pinning efficiency has been obtained for BZO 1D-APCs in 2-8% BZO/YBCO SD-ML samples. The $F_{p,max}$~157 GN/m^3 (65K, 6vol% BZO doping) is 4.4 times of that of the SL counterpart without the interface repair**