RABiTS-Based Strategic Research

OAK RIDGE NATIONAL LABORATORY

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FY 2004 OETD Funding: $900K

Relevance to DOE Superconductivity Program and Technical Targets

"R&D Needs/Knowledge gaps" identified in the DOE Coated Conductor Technology Development Roadmap *and* addressed in this project:

- **Developing solution-based buffers**
- **Development of an all conducting buffer architecture**
- **Non-Ni substrate development**
- **Understanding interfaces between epitaxial layers**
- **Understanding of microstructural factors affecting critical current density**

Specific Objectives/Milestones

- **Develop all solution buffer architectures that are compatible with MOD TFA YBCO**
  - Achieve over 200 A/cm-w on solution LZO seeds
  - Extend to 4-cm-wide substrates

- **Continue fundamental studies of epitaxial growth of both PVD and solution buffers on textured substrates, including copper and copper alloys.**

- **For copper-based substrates, develop a fully conductive architecture. Achieve high-*I*c YBCO films on Cu or Cu-alloy templates by *in-situ* or *ex-situ* approach.**

- **Enhance flux-pinning in YBCO films on RABiTS through growth-controlled pinning centers**

Research Integration (scoring criterion)

Close Collaboration with University of Tennessee

Two Research Assistant Professors working full time at ORNL

- **Tolga Aytug**
- **S. Sathyamurthy (Watson)**

Presentation Outline

- **FY 2004 Results**

  Solution-based buffer layers **(Watson)**

  Development of all conducting buffer layers (Tolga)

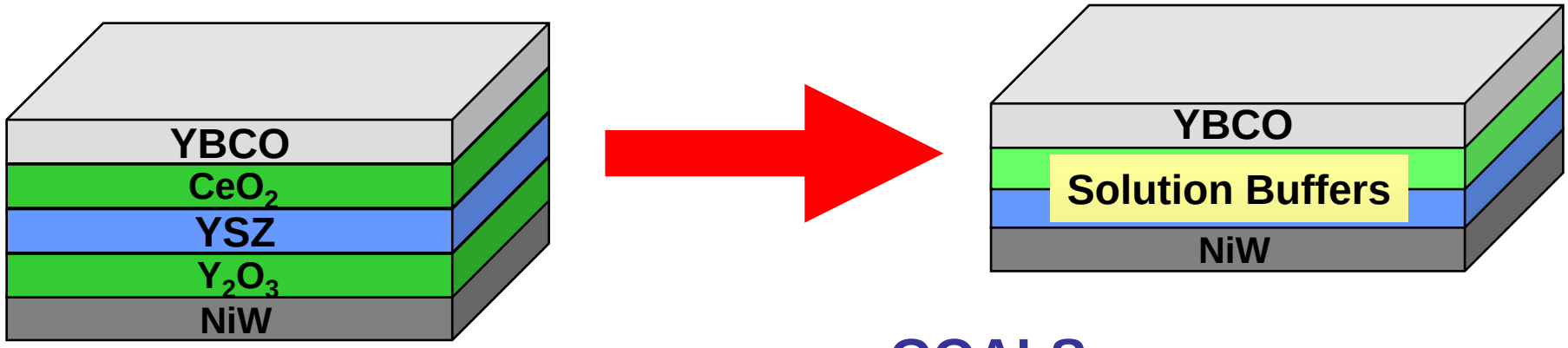
  Incorporation of pinning centers in YBCO films on RABiTS (Amit)

  Status of Cu-based substrates (Amit)

- FY 2004 Performance and FY 2005 Plans (Amit)

- Research Integration

Solution Based Buffer Layers



Deposition Methods:

- YBCO: ex-situ BaF_2 (or TFA)
- YSZ and CeO_2 : rf sputtering
- Y_2O_3: e-beam

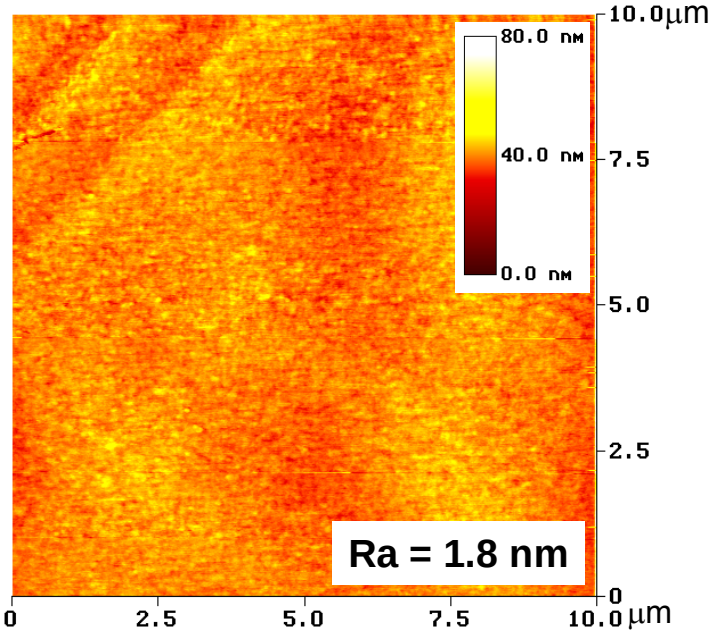
GOALS

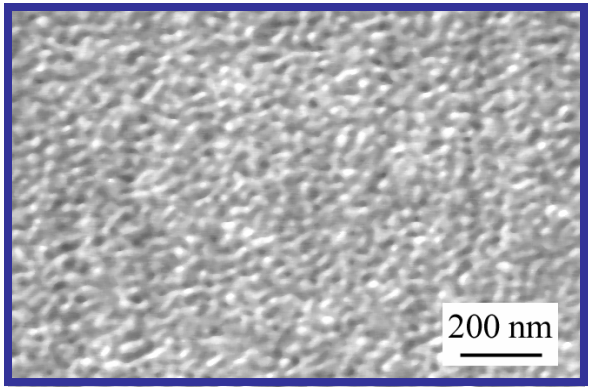
- Simplified buffer architecture
- Potentially lower cost
- Faster deposition
- Compatible with ex-situ BaF_2 (or TFA)

Materials under consideration
$La_2Zr_2O_7$ (LZO) and CeO_2

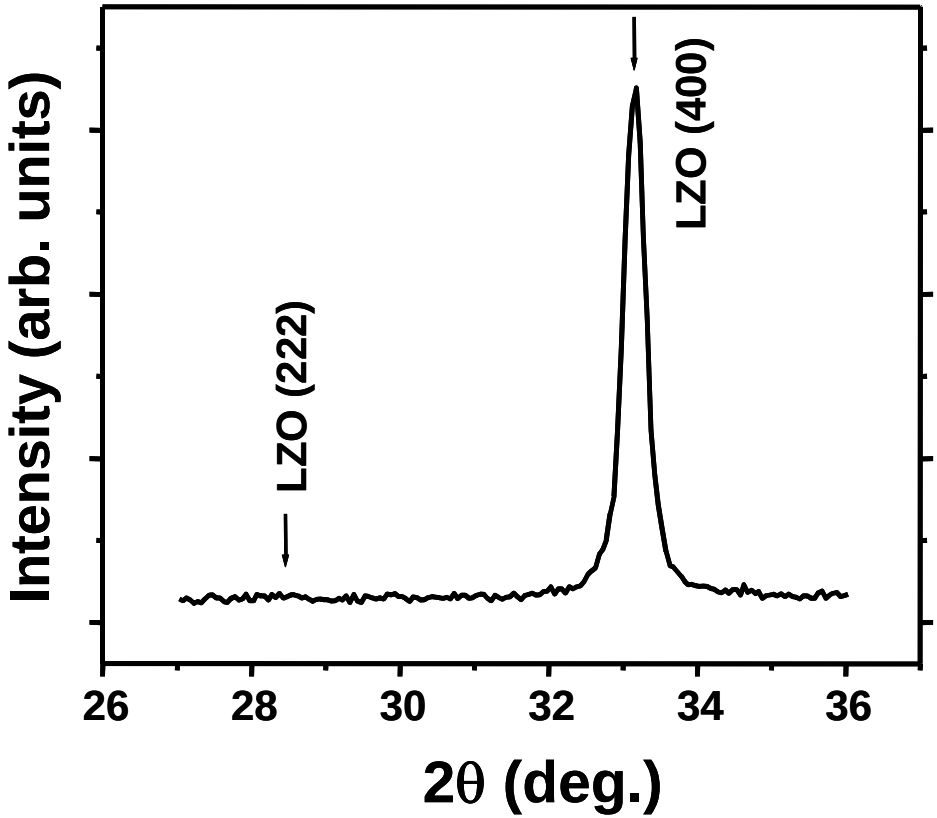
Solution Buffer Layer Development

AFM LZO surface





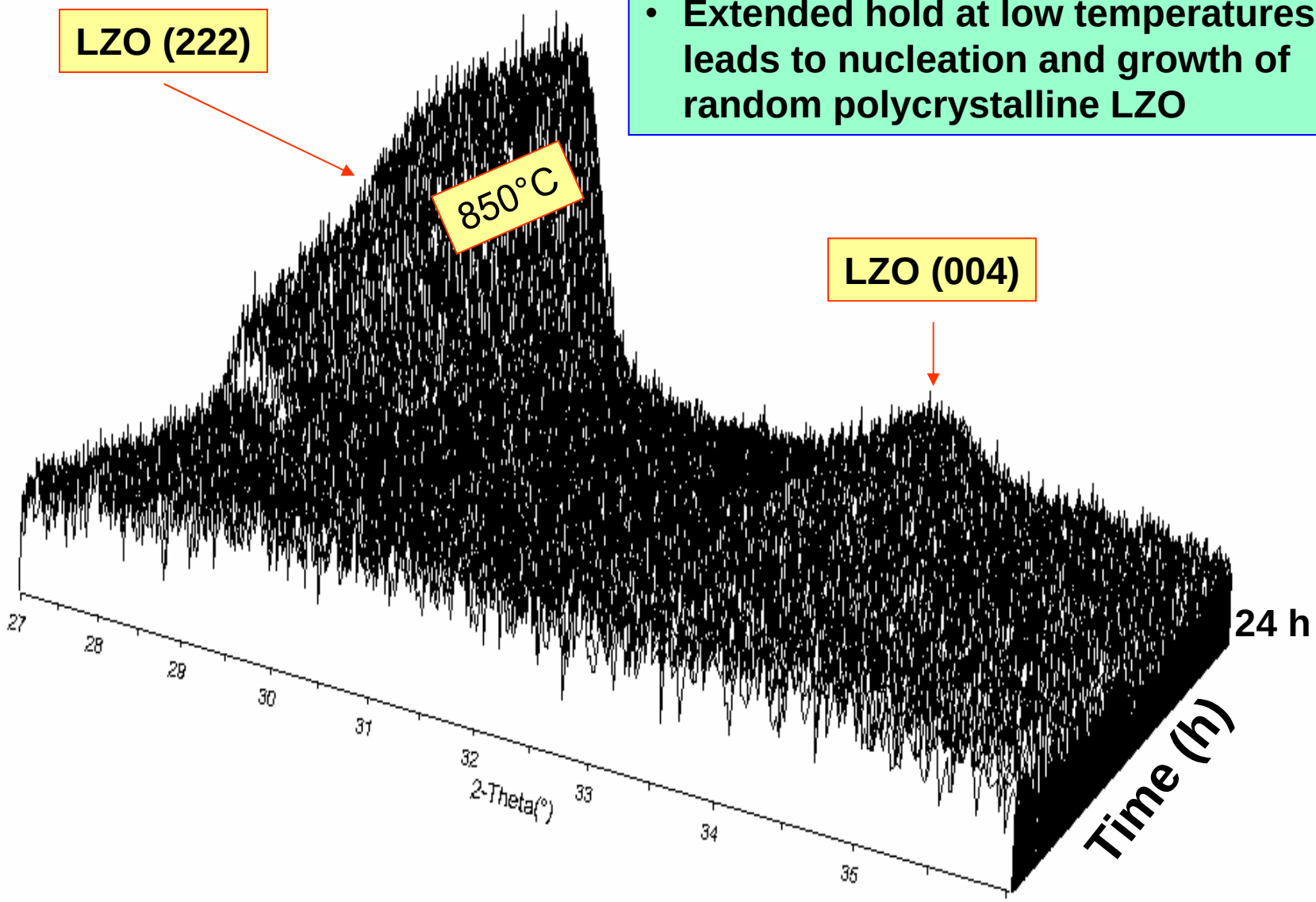
SEM LZO surface



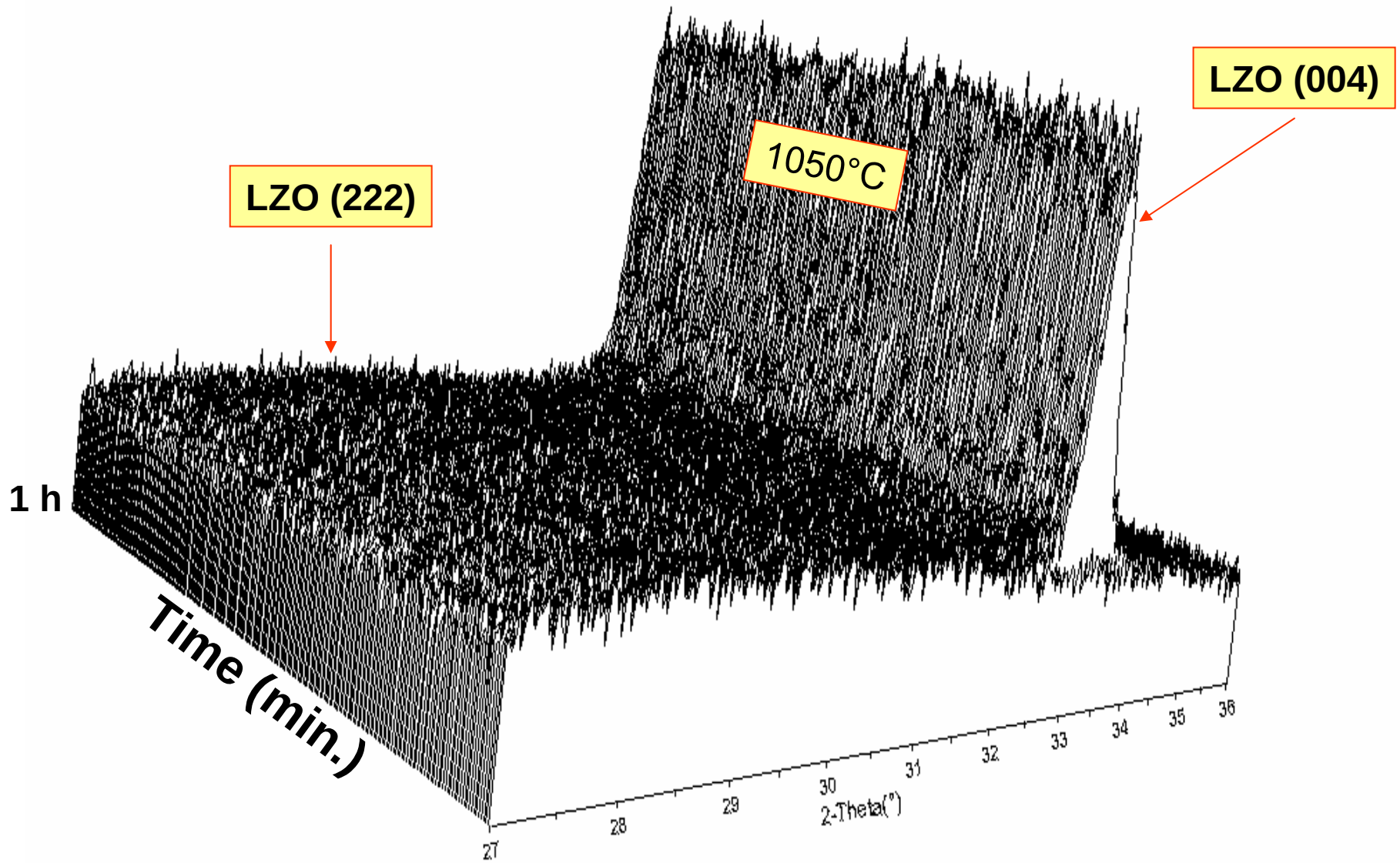
- Epitaxial LZO with smooth surface can be grown directly on textured Ni-W substrates
- 20 – 100 nm/coat; highly reproducible
- Pursued reel-to-reel dip-coating for double sided conductors

Nucleation and Growth Kinetics of sol-gel LZO films on Ni-W substrates

- **Extended hold at low temperatures leads to nucleation and growth of random polycrystalline LZO**



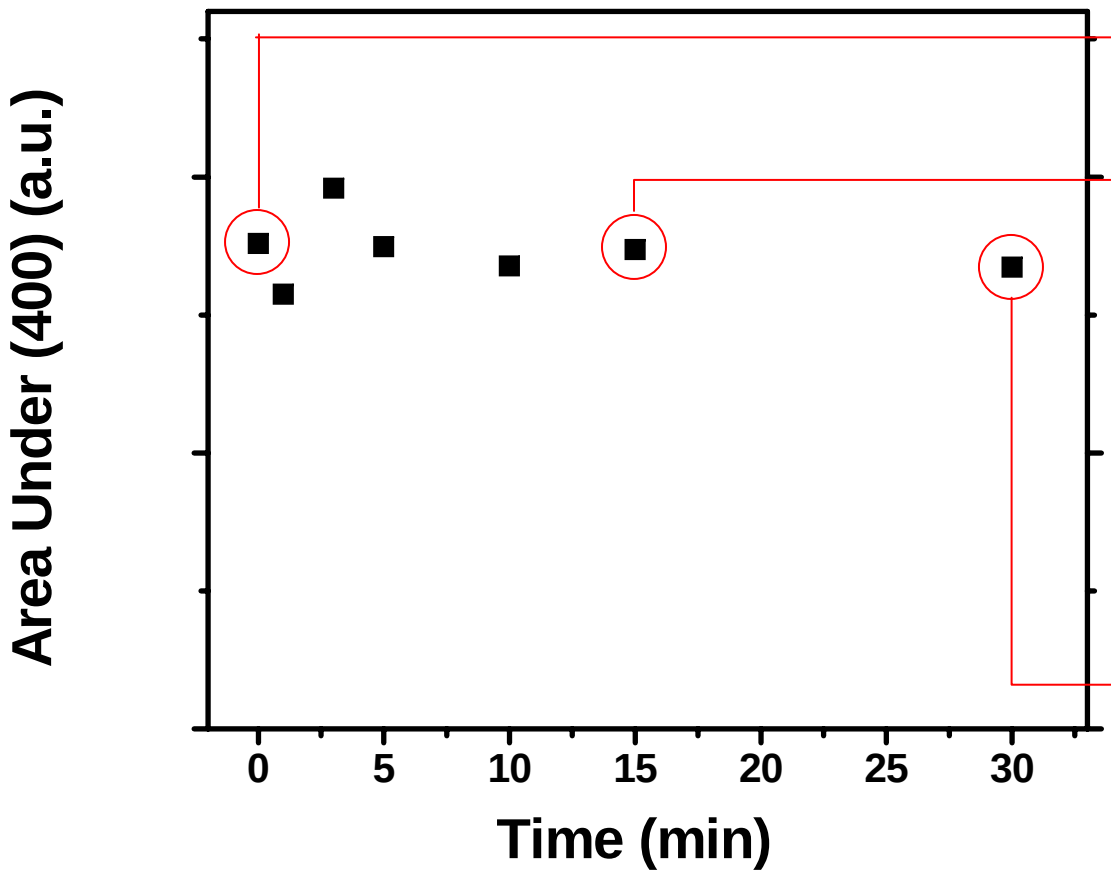
Epitaxial LZO films can be processed at high rates at high temperatures

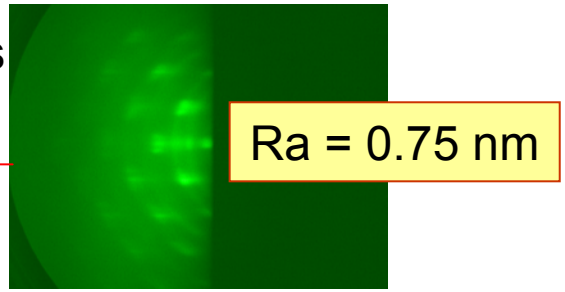


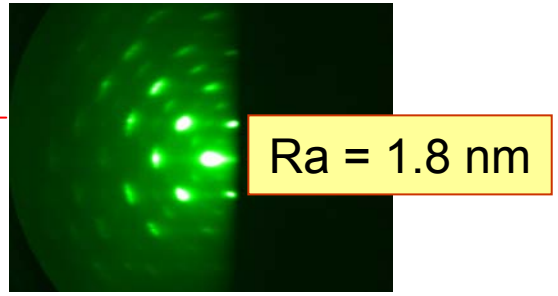
UT-BATTELLE

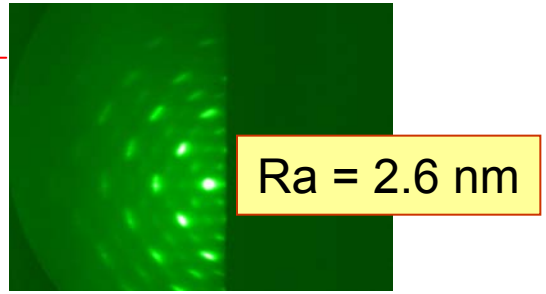
Thick LZO films with good surface crystallinity and smooth surface can be processed at high rates

100 nm LZO films processed at 1100°C for different times

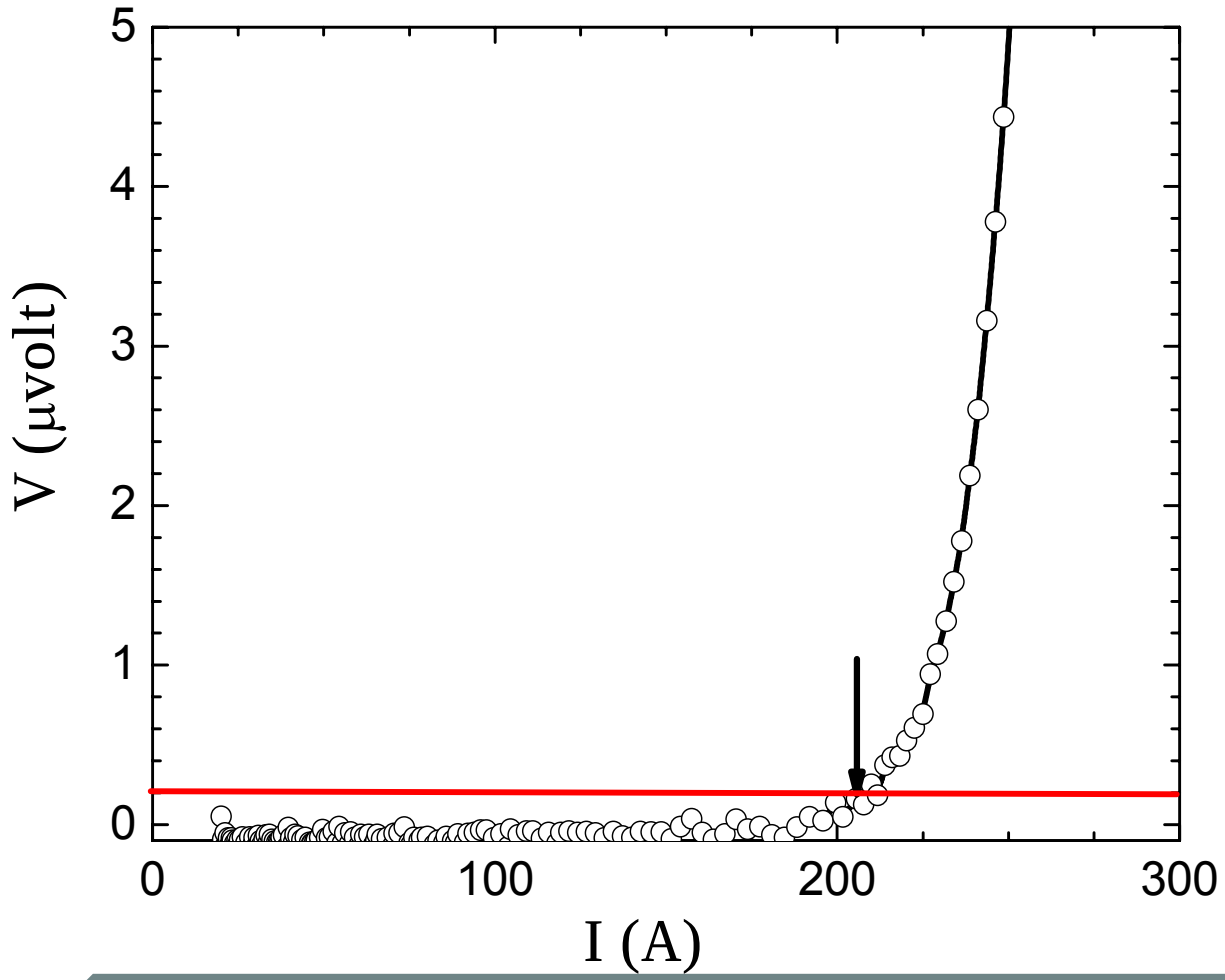


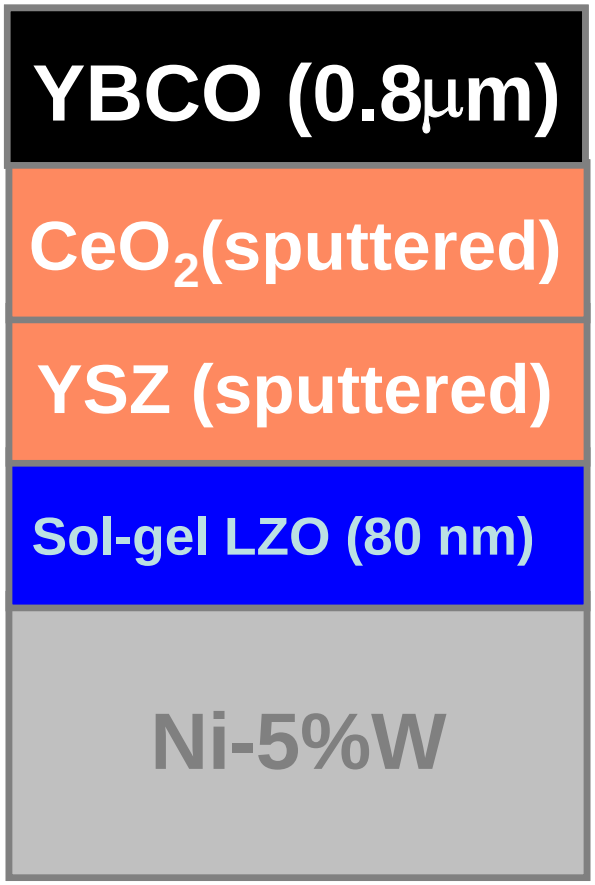






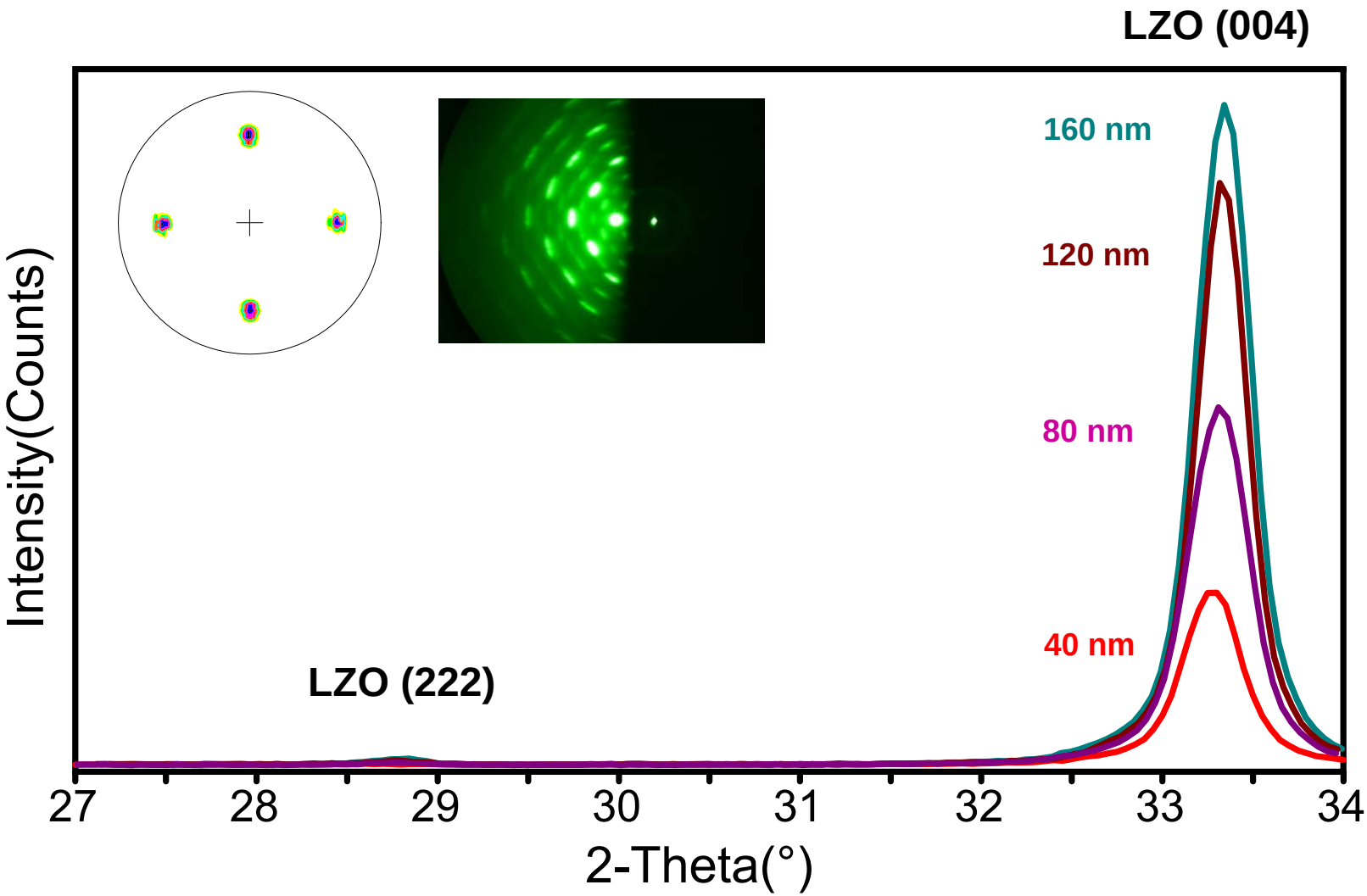
Milestone met : I_c > 200 A/cm achieved on solution seed layers





77K, sf J_c=2.7 MA/cm², I_c=213 A/cm; $T_c(0)$ = 90.1 K, ΔT_c=1.2 K

Effect of LZO thickness for high J_c YBCO



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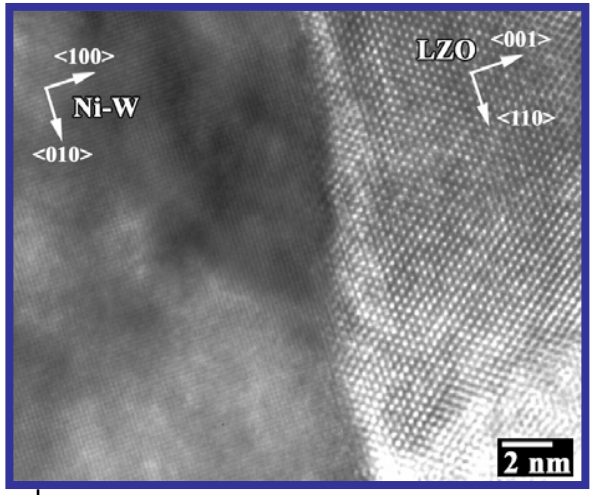
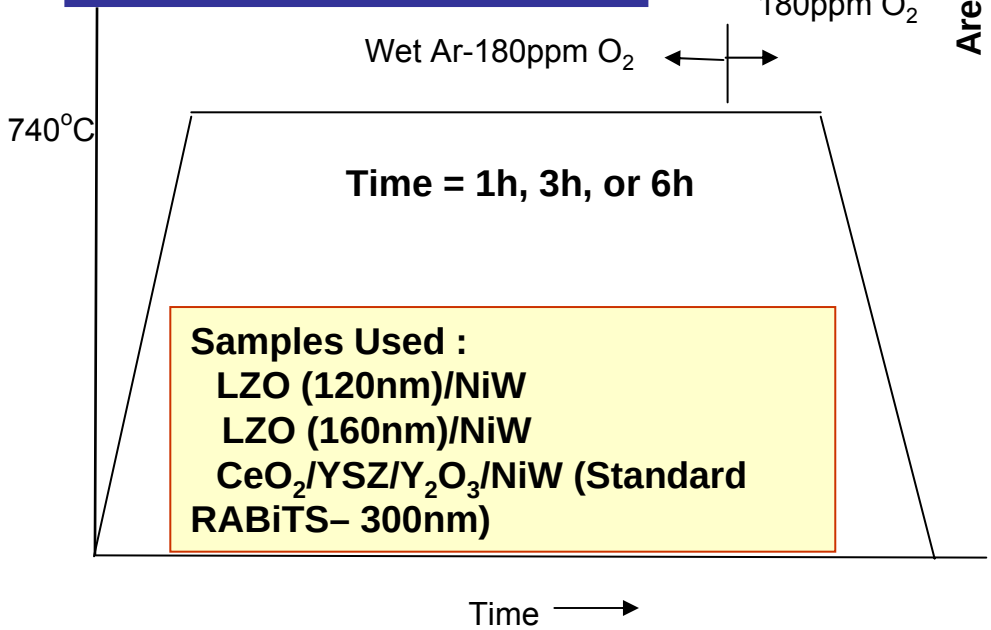
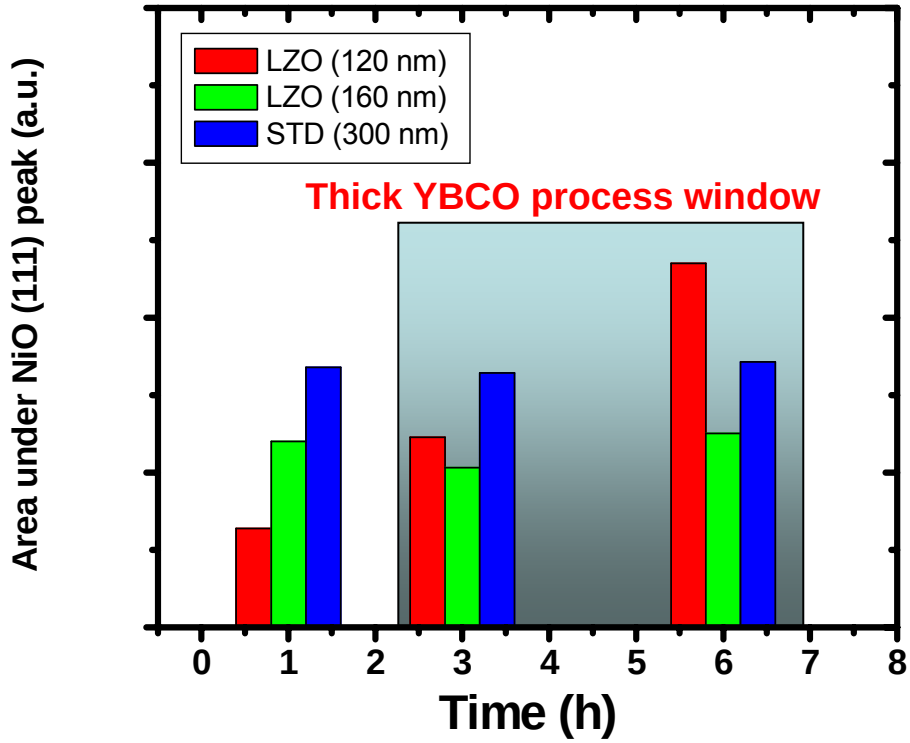
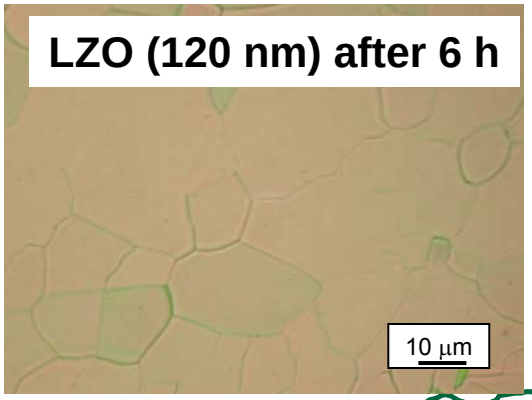
Thicker LZO film protects the nickel from extensive oxidation



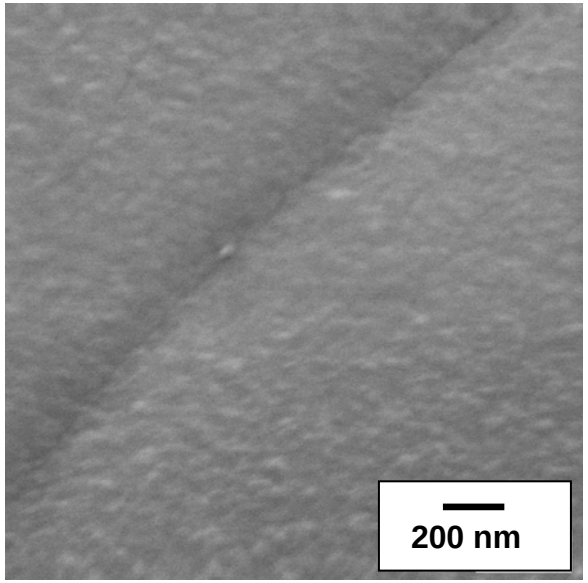


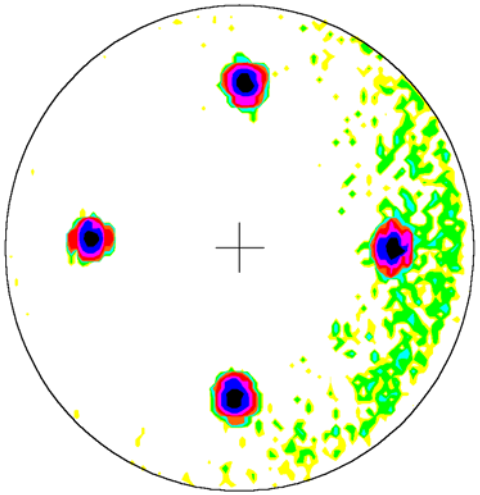
Samples Used :
- **LZO (120nm)/NiW**
- **LZO (160nm)/NiW**
- **CeO_2/YSZ/Y_2O_3/NiW (Standard RABiTS– 300nm)**





MOD approach gives epitaxial CeO_2 with smooth surface, dense microstructure, and improved texture

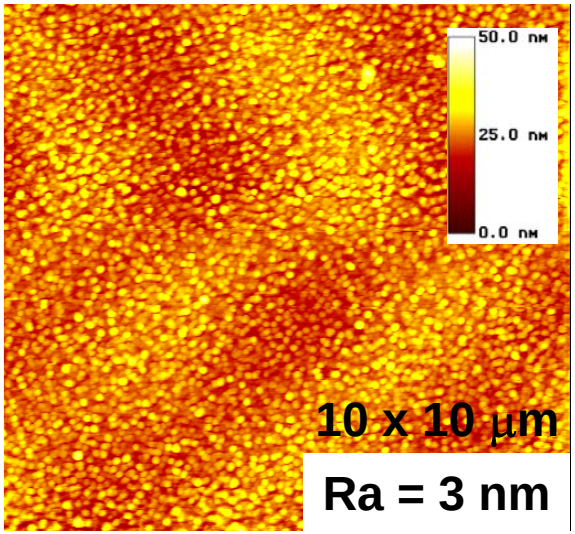


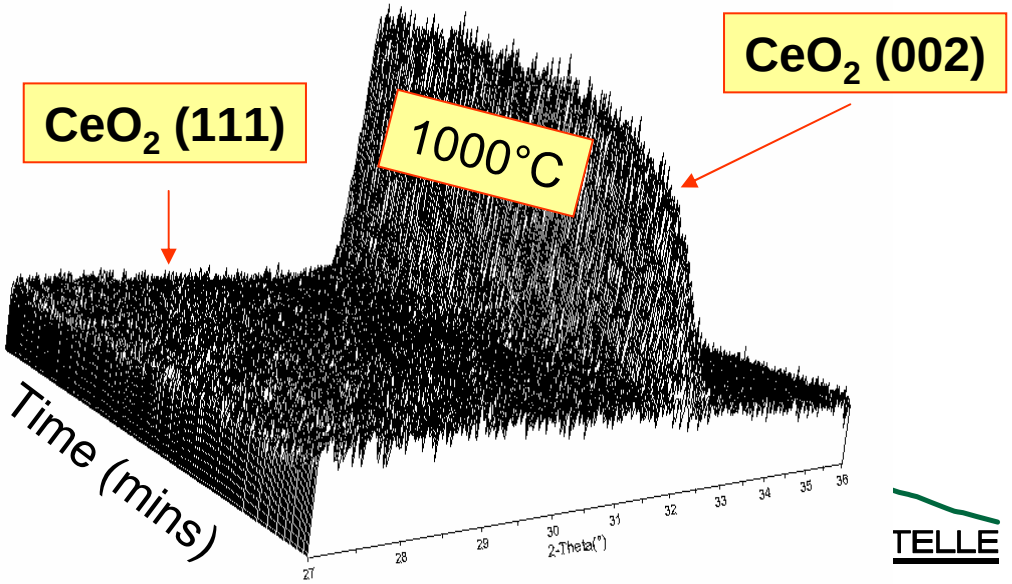


Texture

	$\Delta\omega$	$\Delta\phi$
CeO_2	4.7^o	7.4^o
NiW	5.2^o	7.4^o

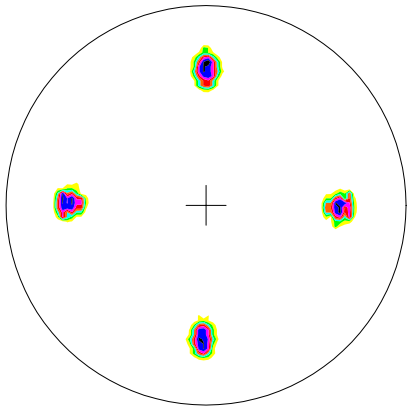
- **Process time <15 mins at temperatures >1000°C**

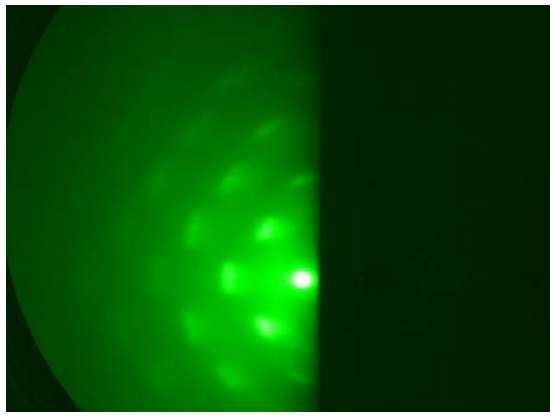




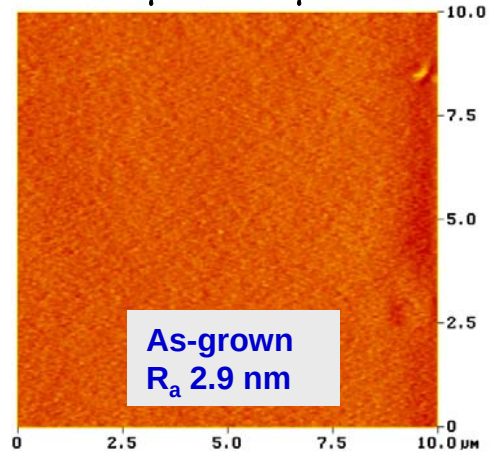
TELLE

Solution CeO_2 with good texture and smooth surface deposited on LZO/NiW



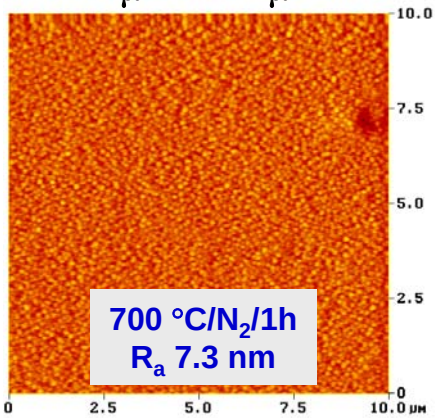


10 μm x 10 μm

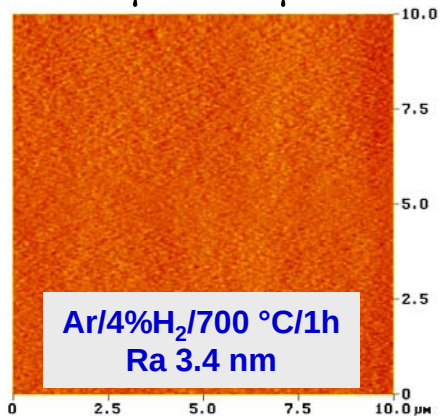


- Effect of annealing treatments

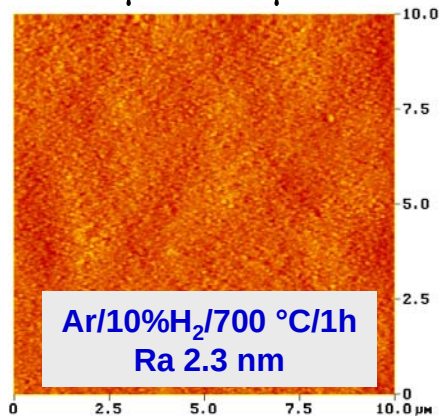
10 μm x 10 μm



10 μm x 10 μm



10 μm x 10 μm



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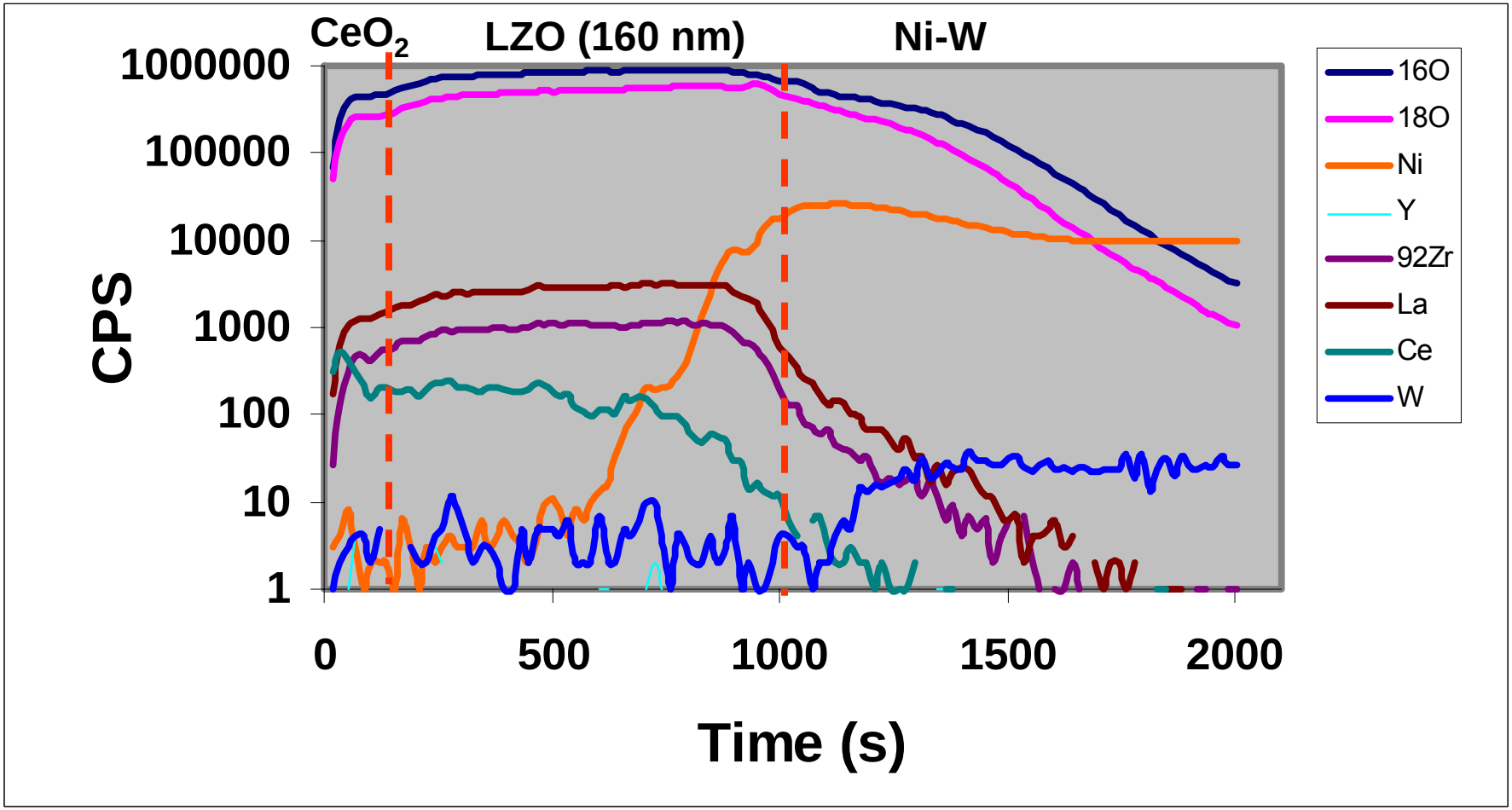
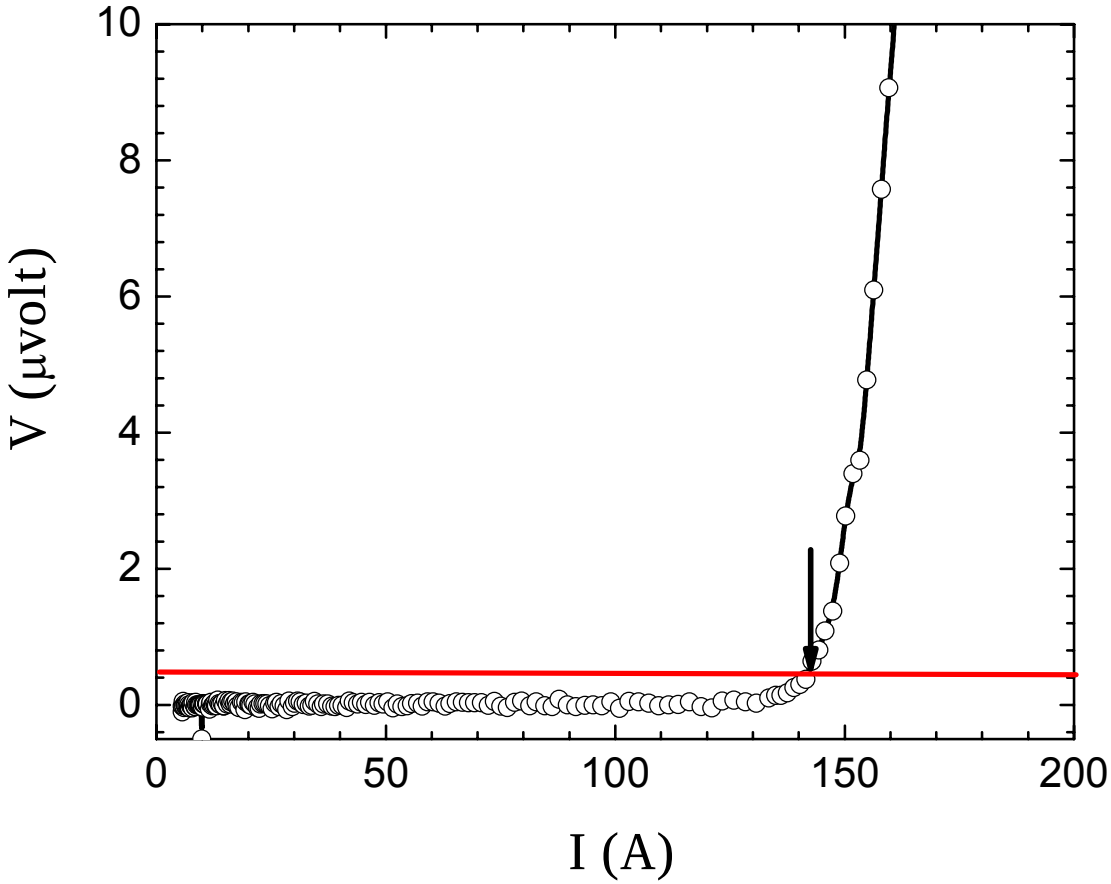
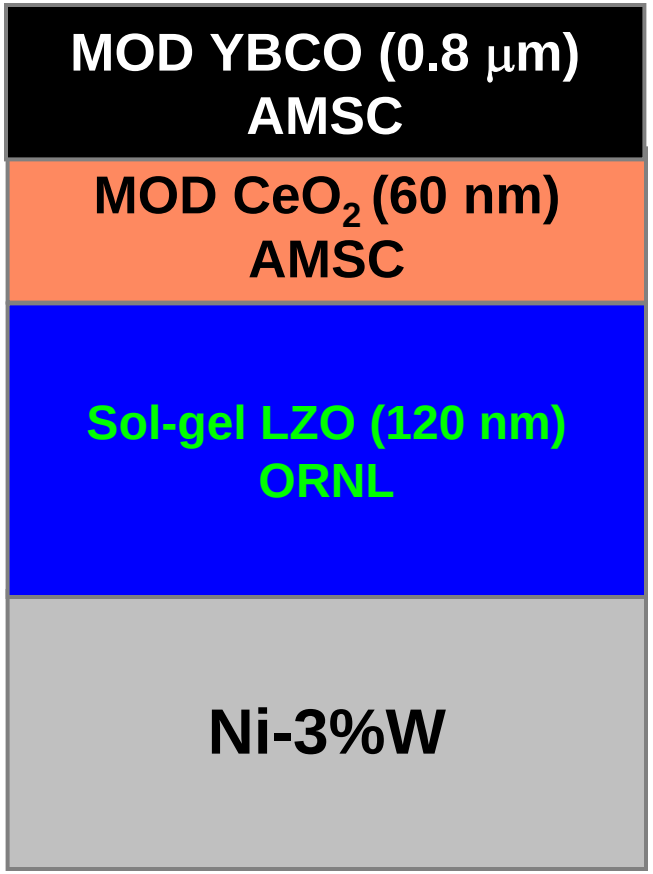
SIMS studies on all-solution buffer architecture shows Ni diffusion is blocked successfully



UT-BATTELLE

I_c of 140 A/cm demonstrated for the first time for solution YBCO on all-solution buffers





77K, SF: J_c = 1.75 MA/cm^2, I_c = 140 A/cm

Summary

- Epitaxial LZO films with smooth surface can be grown by sol-gel processing
- Demonstrated I_c = 213 A/cm-w using solution LZO seed layers - YBCO (0.8 μm – MOD)/ CeO_2 (sputt.) / YSZ (sputt.) / LZO (80 nm) / Ni-W
- Solution LZO > 80 nm is effective in stopping Ni diffusion
- Solution CeO_2 can be grown on solution LZO with good texture and smooth surface
- Demonstrated I_c = 140 A/cm-w using all solution conductors
  YBCO (0.8 μm – MOD) / CeO_2 (60 nm - MOD) / LZO (120 nm – sol-gel) / Ni-W

Presentation Outline

- FY 2004 Results

  Solution-based buffer layers (Watson)

  Development of all conducting buffer layers (Tolga)

  Incorporation of pinning centers in YBCO films on RABiTS (Amit)

  Status of Cu-based substrates (Amit)

- FY 2004 Performance and FY 2005 Plans (Amit)

- Research Integration

Development of Conductive Buffer Layers for RABiTS-based Coated Conductors

Project Objective:

Develop multifunctional electrically conductive buffer layers for advanced coated conductors

Approach:

- Identify issues & develop a proof-of-principle conductive buffer architecture on Ni-3at.%W substrates
- Use understanding achieved from the Ni-alloy tapes to apply the same approach on pure textured Cu substrates

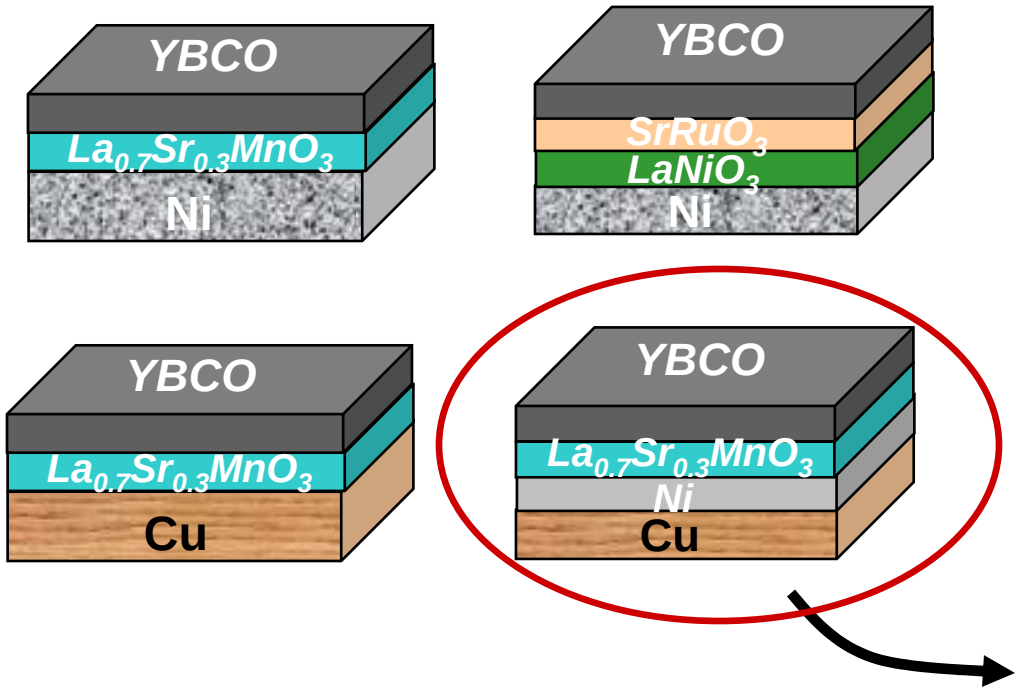
Motivation for Cu-based substrates:

- Non-magnetic (no ferromagnetic *ac*-losses)
- Lower cost (commodity prices a factor of 4-6 less than Ni)
- High thermal conductivity
- High electrical conductivity
  - ➥ Electrical self-stabilization
  - ➥ Substantial improvement in J_E

Development of Conducting Buffer Layers are Challenging due to the Oxidation of the Substrate

Electrical coupling degrades due to interfacial NiO or Cu-O formation

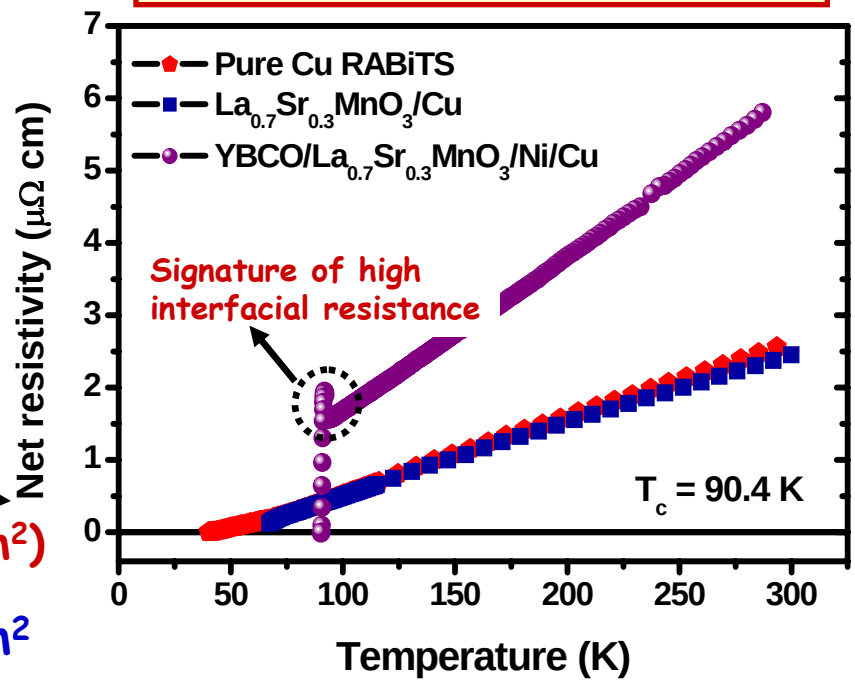
Previous work on conductive buffer architectures:



(effective R_i ~ 1 x 10^{-5} Ω-cm²)

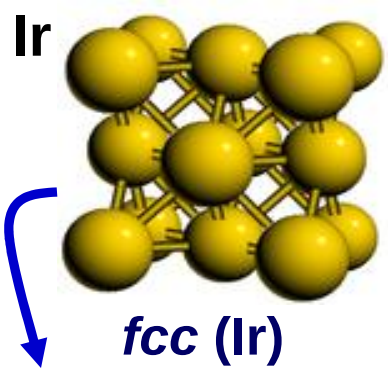
For applications, need R_i < 10^{-7} Ω-cm²

J_c (77 K,0 T) = 2.3 x 10^6 A/cm²

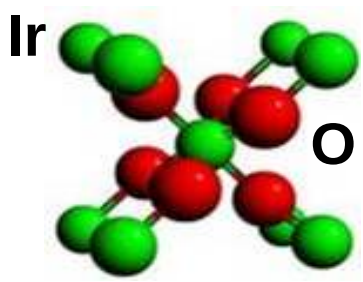


Oxygen Diffusion Barrier Needed for YBCO Deposition

Conducting seed layer, preferably having a conductive native oxide is desirable



fcc (Ir)



Rutile (IrO_2)

- Conductive oxide [ρ (RT) < 50 μΩ cm)]
- Tetragonal, lattice parameter (a_o = 4.49 Å)

- Conductive metal [ρ (RT) < 5 μΩ cm)]
- Non-magnetic
- Cubic, close lattice match to YBCO (a_o = 3.84 Å)
- High density = 22.4 g/cc & Melting point= 2716 K

Main use in industry

Oxygen stable electrodes in corrosive environments

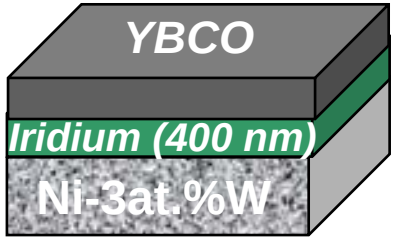
Oxygen diffusion coefficients

Material	Oxygen diffusion (cm^2/sec) 800 °C
MgO	8×10^{-22}
$LaMnO_3$	7.7×10^{-15}
$La_{0.7}Sr_{0.3}MnO_3$	5×10^{-15}
IrO_2	6×10^{-15}
Ir	5×10^{-12}
Y_2O_3	6×10^{-10}
CeO_2	6×10^{-9}
YSZ	2×10^{-8}

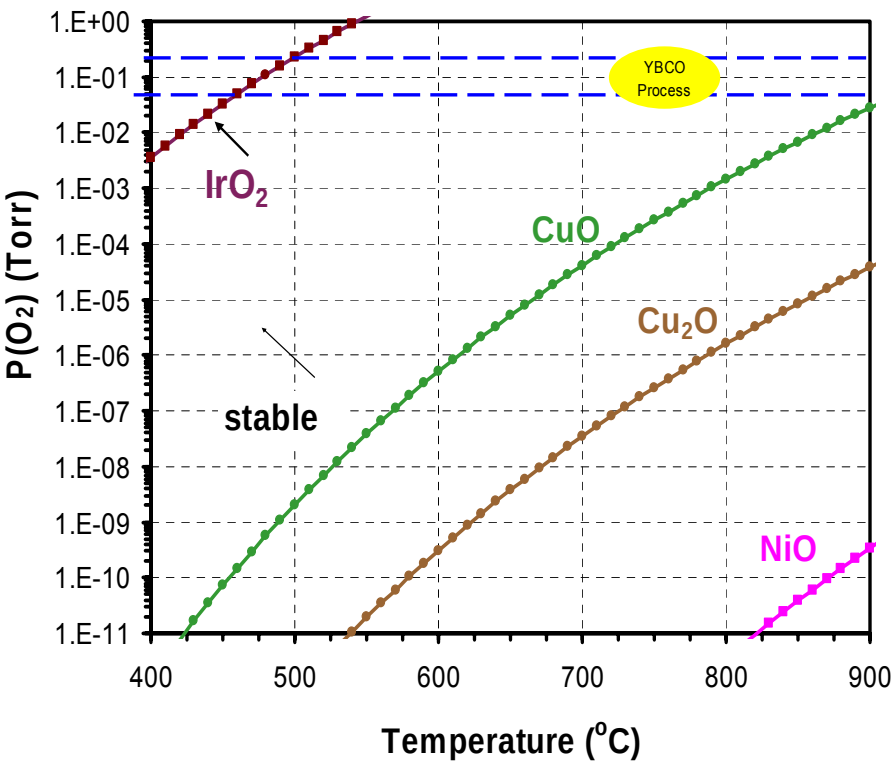
Post-annealing Studies in Simulated YBCO Dep. Conditions

As suggested by thermodynamic stability consideration:

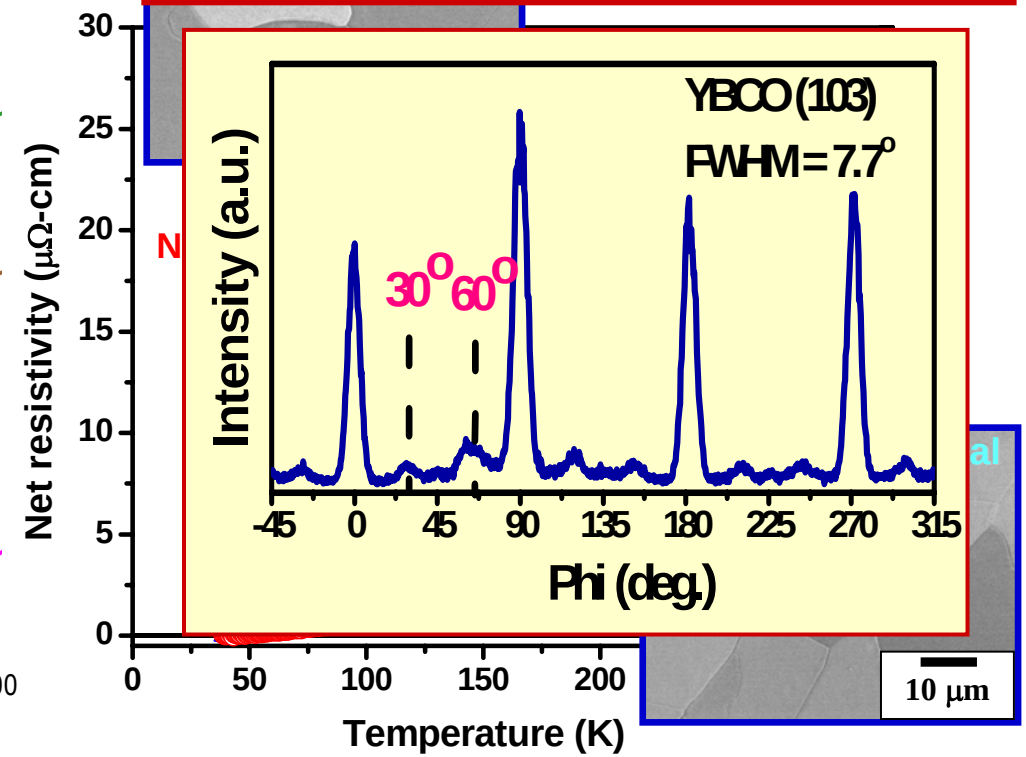
- XRD shows no IrO_2 formation
- No NiO due to low oxygen diffusion through Ir
- ρ vs T shows complete electrical coupling



T=780 °C & $P(O_2)$= 100 mTorr, Time= 15 min.

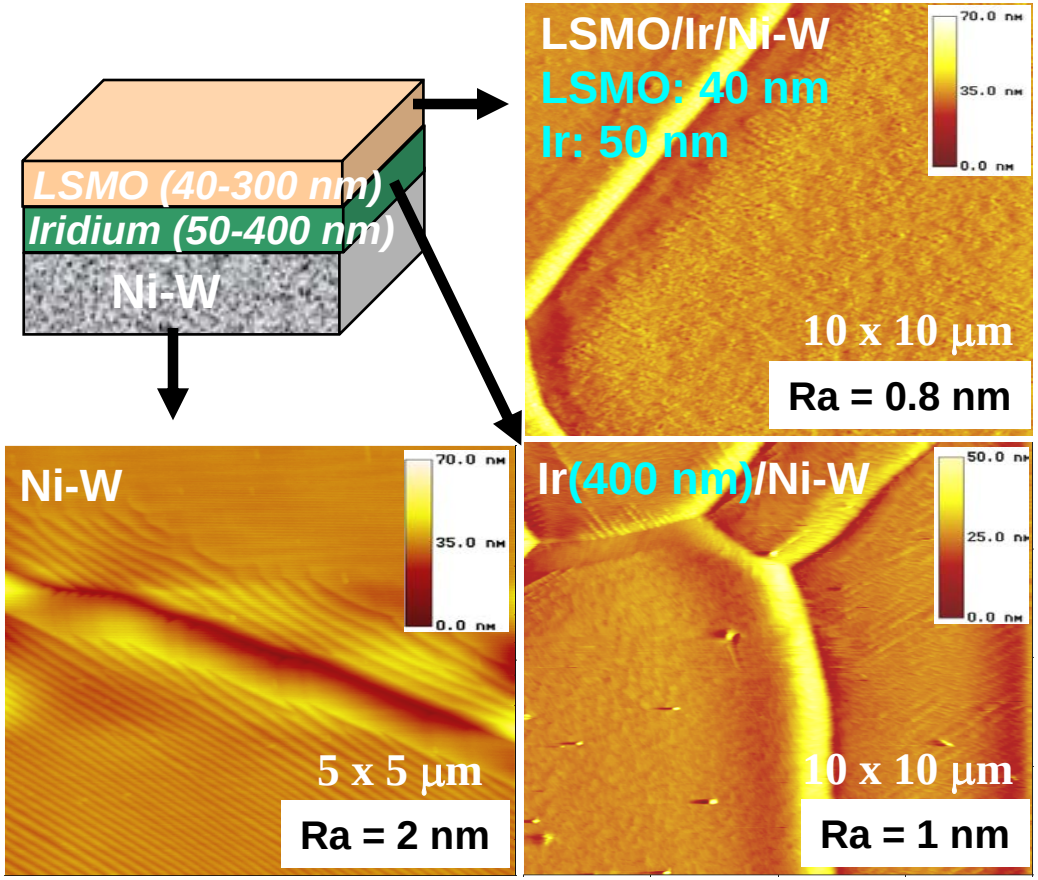


Limited J_c performance, directly on Ir, is due to the multiple domain oriented YBCO

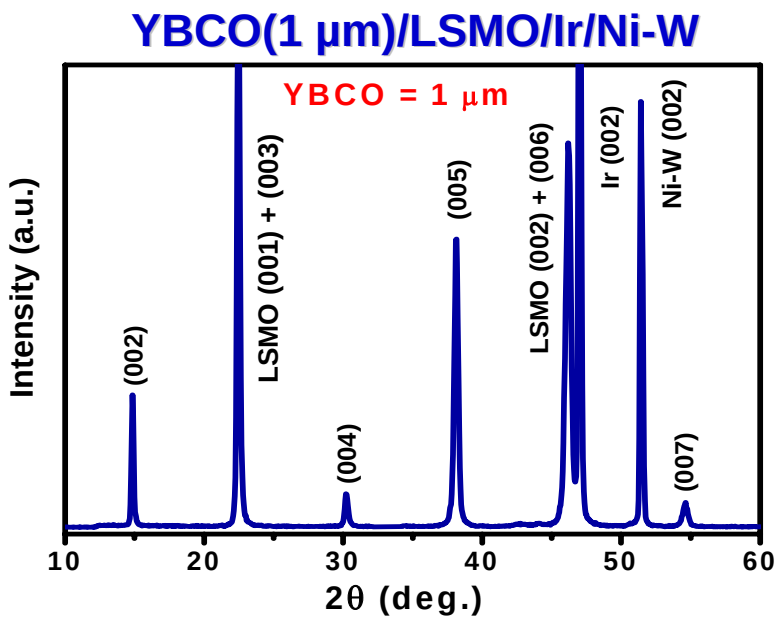


Conductive $La_{0.7}Sr_{0.3}MnO_3$ Cap Layers Enabled Growth of High-Quality PLD-YBCO Films on Ir/Ni-W

Improved surface roughness with Ir

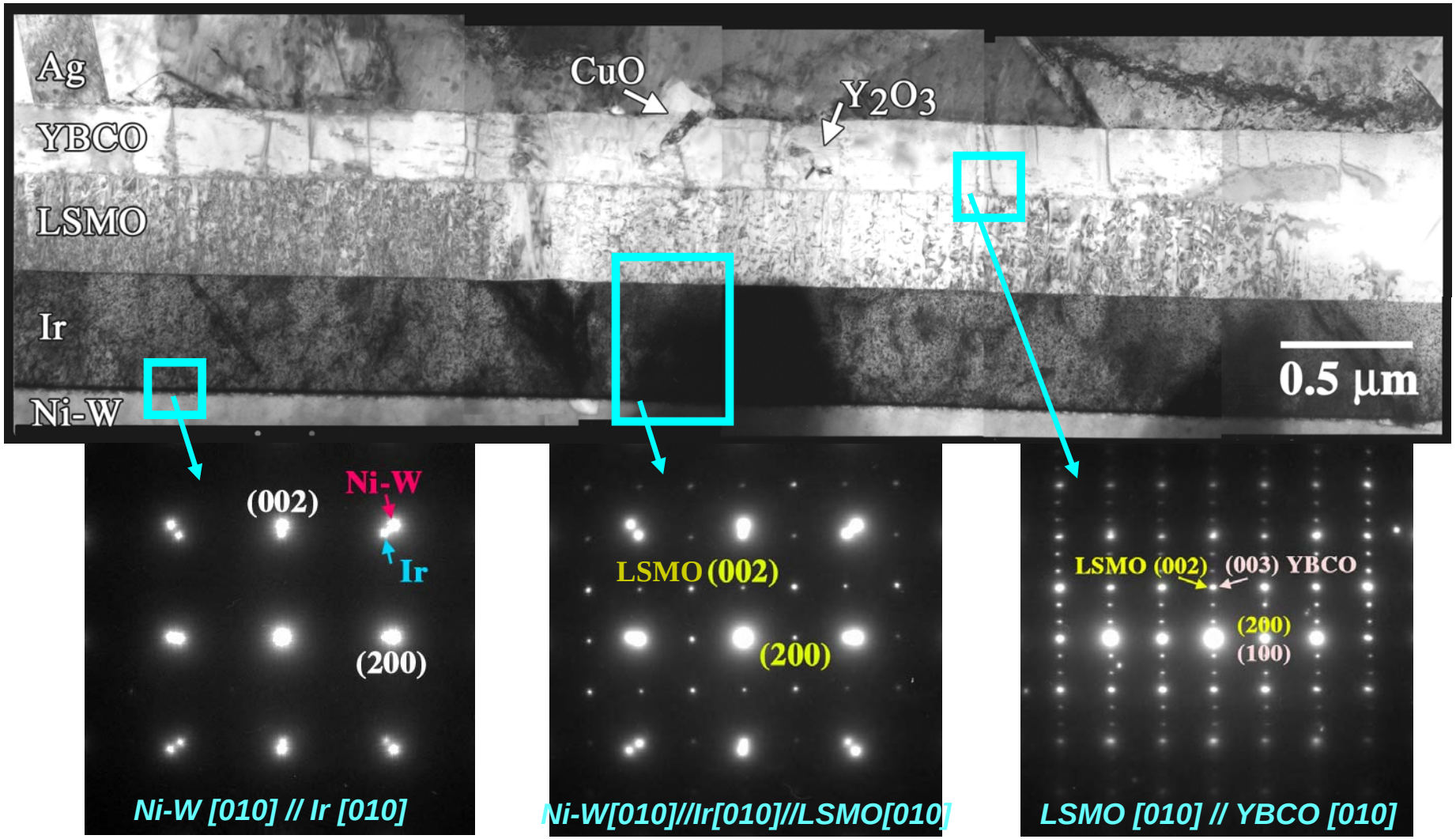


A totally insulating-oxide-free RABiTS architecture obtained



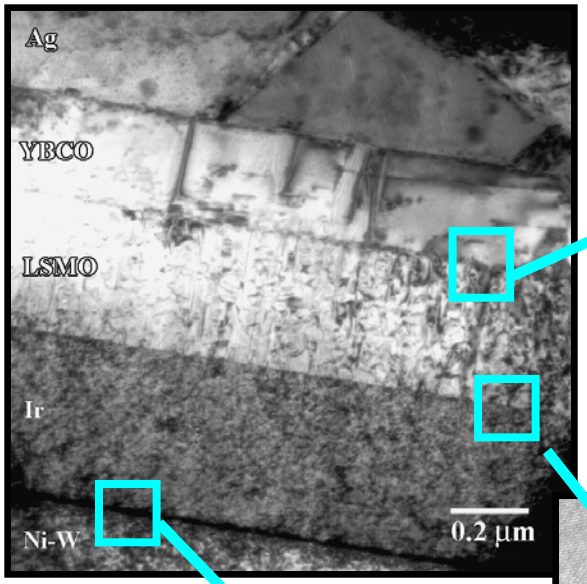
- Fully epitaxial architecture obtained
- No NiO, $NiWO_4$, IrO_2 at interface
- No other reaction phases even after 1µm YBCO growth

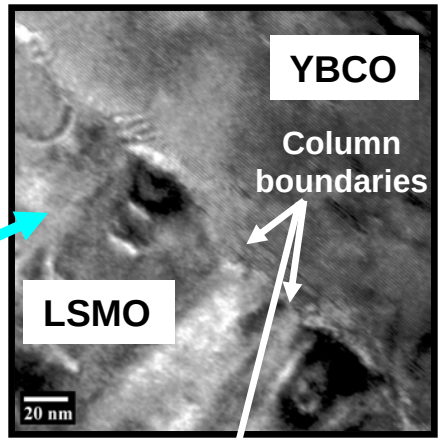
TEM of PLD-YBCO(0.2 µm)/LSMO/Ir/Ni-W

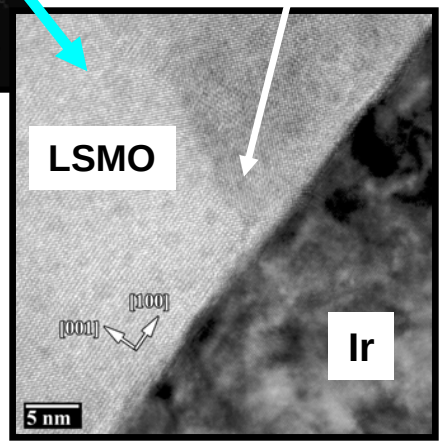


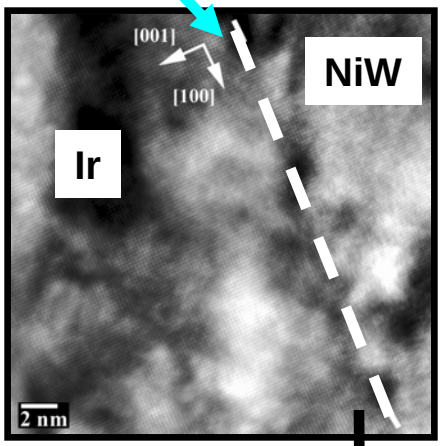
- All interfaces are clean & sharp; no NiO & $NiWO_4$ & no interdiffusion
- YBCO/LSMO/Ir/Ni-W layers are epitaxial & cube-on-cube oriented

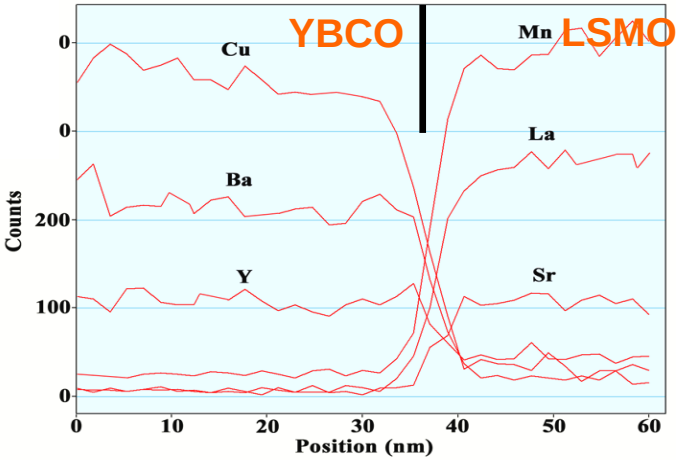
HRTEM YBCO(0.2µm)/LSMO/Ir/Ni-W

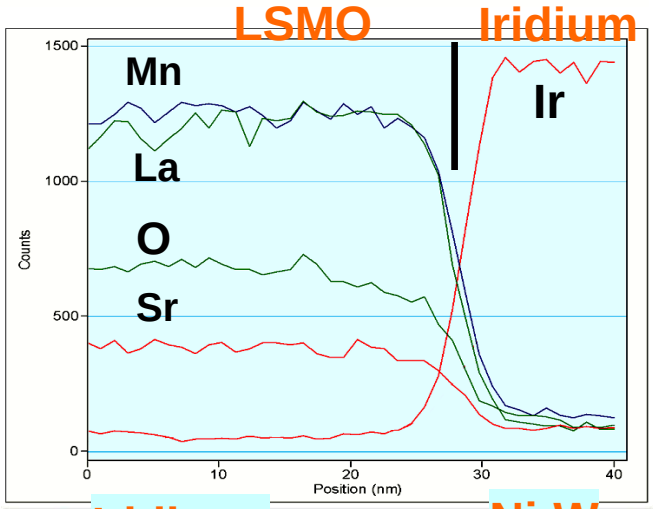


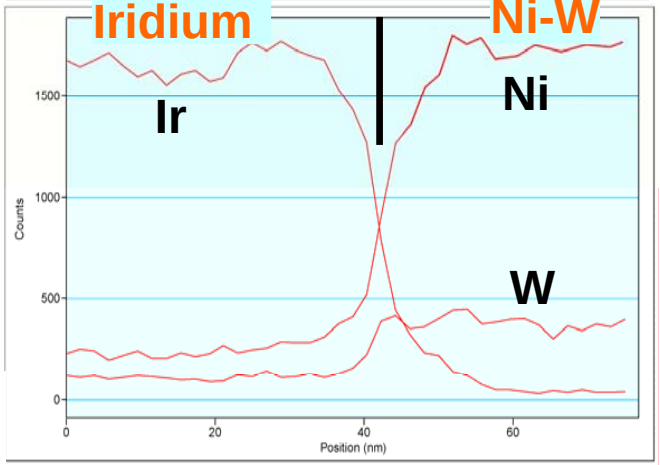












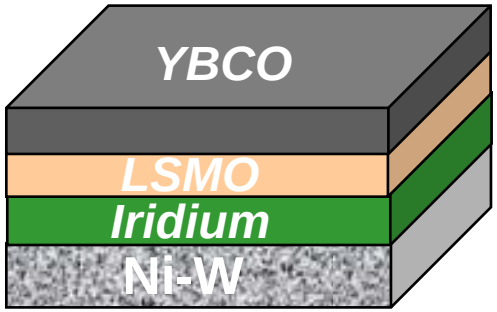
High-resolution EDS line scans reveal:

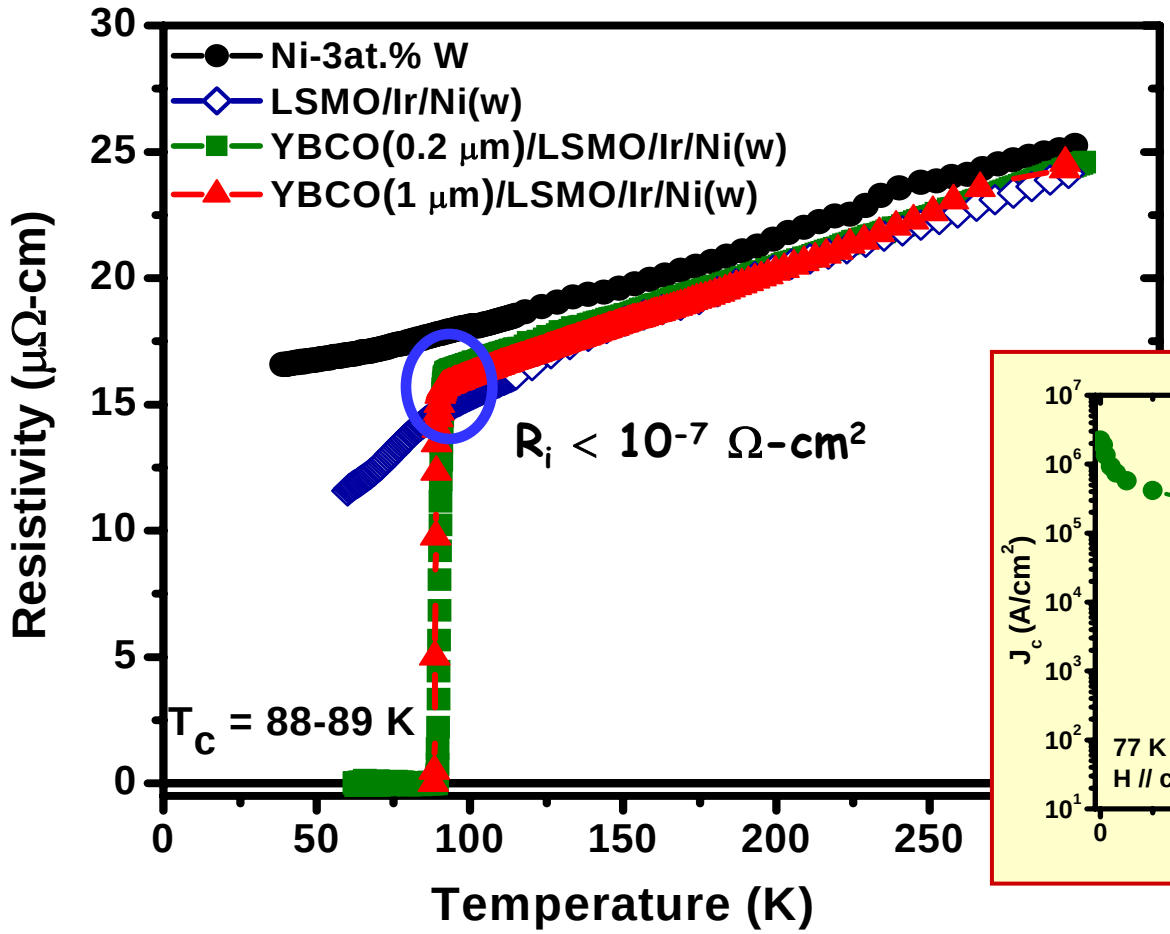
- Absence of oxygen within the Ir, NiW & at the interface
- All interfaces clean. Ir, LSMO blocks inward oxygen diff.

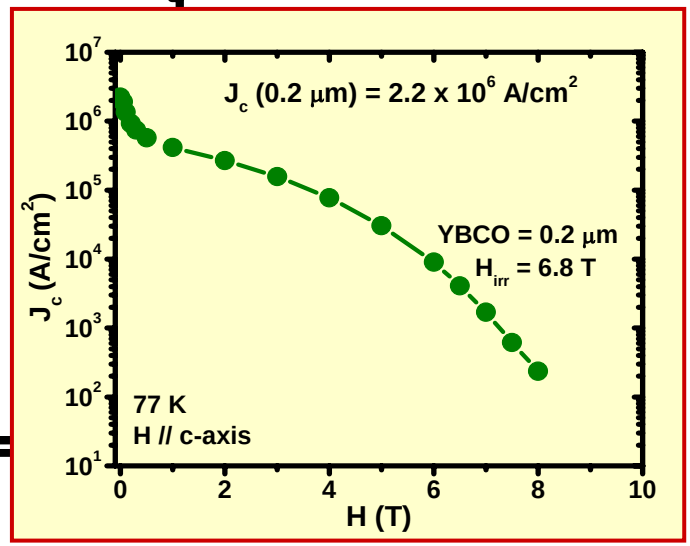
Prototype on Ni-W: A fully conductive architecture is obtained

Excellent electrical coupling among the individual layers

- High-J_c (0.2 μm) = 2.2 x 10^6 A/cm^2
- High-J_c (1 μm) = 1 x 10^6 A/cm^2







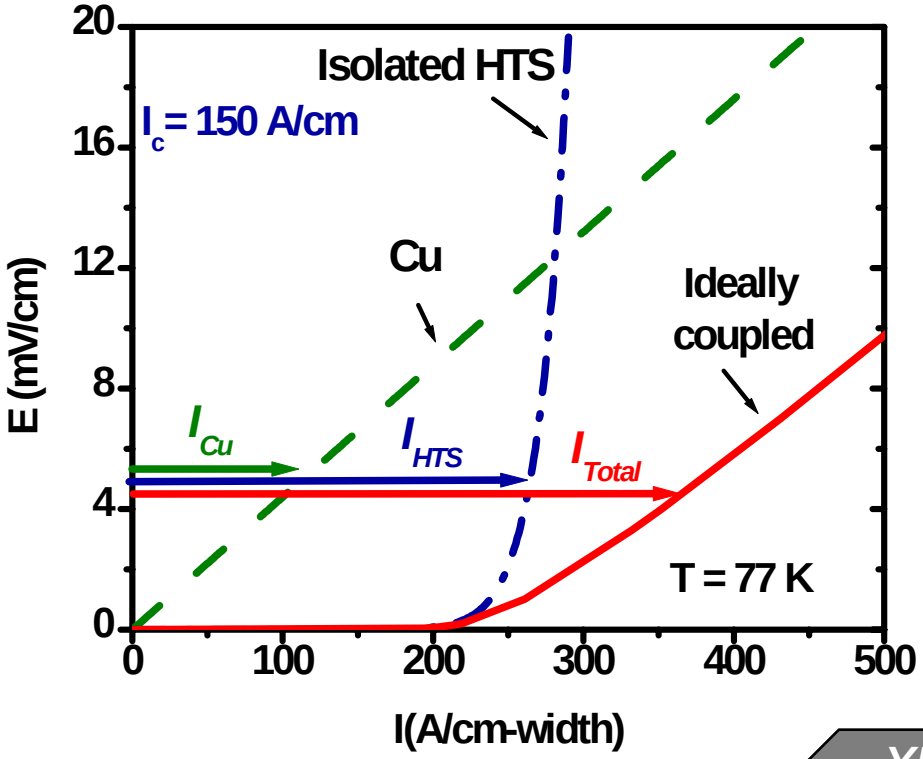
T-BATTELLE

Voltage-Current Characteristics of Conductive *YBCO(0.2 μm)/LSMO/Ir/Ni-W* Structure

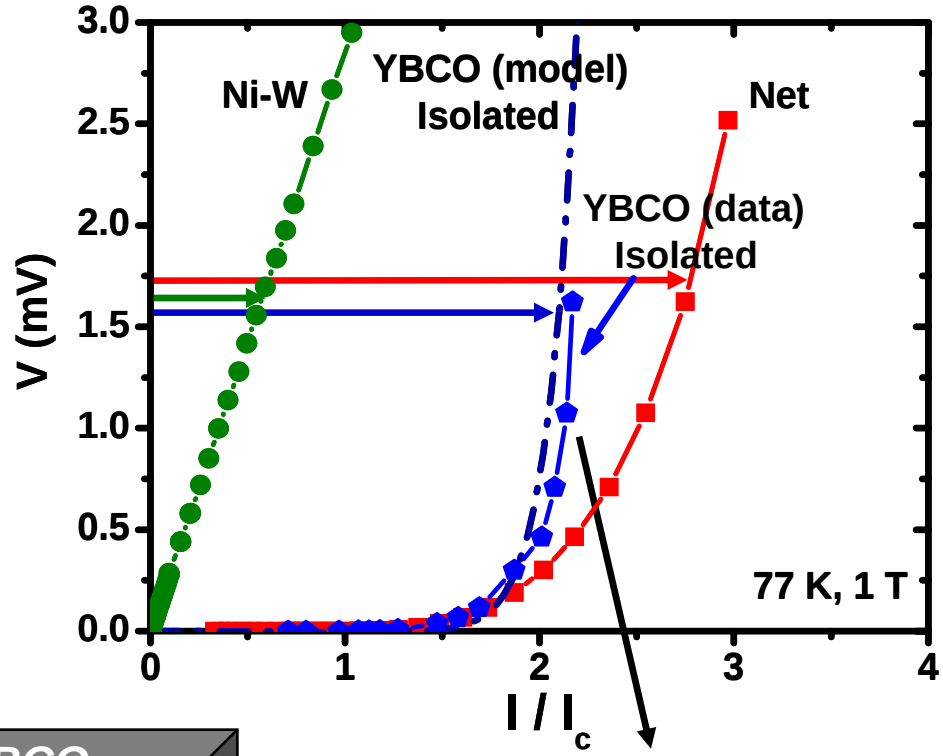
Electrical stability to an over current of ~ $3I_c$ is provided @ H=1 T

Model conductor

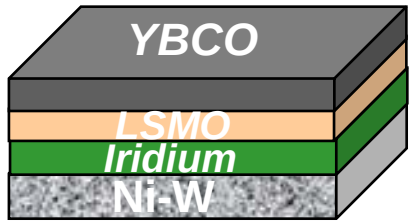
Envisioned for a 50 μm Cu tape



Actual sample



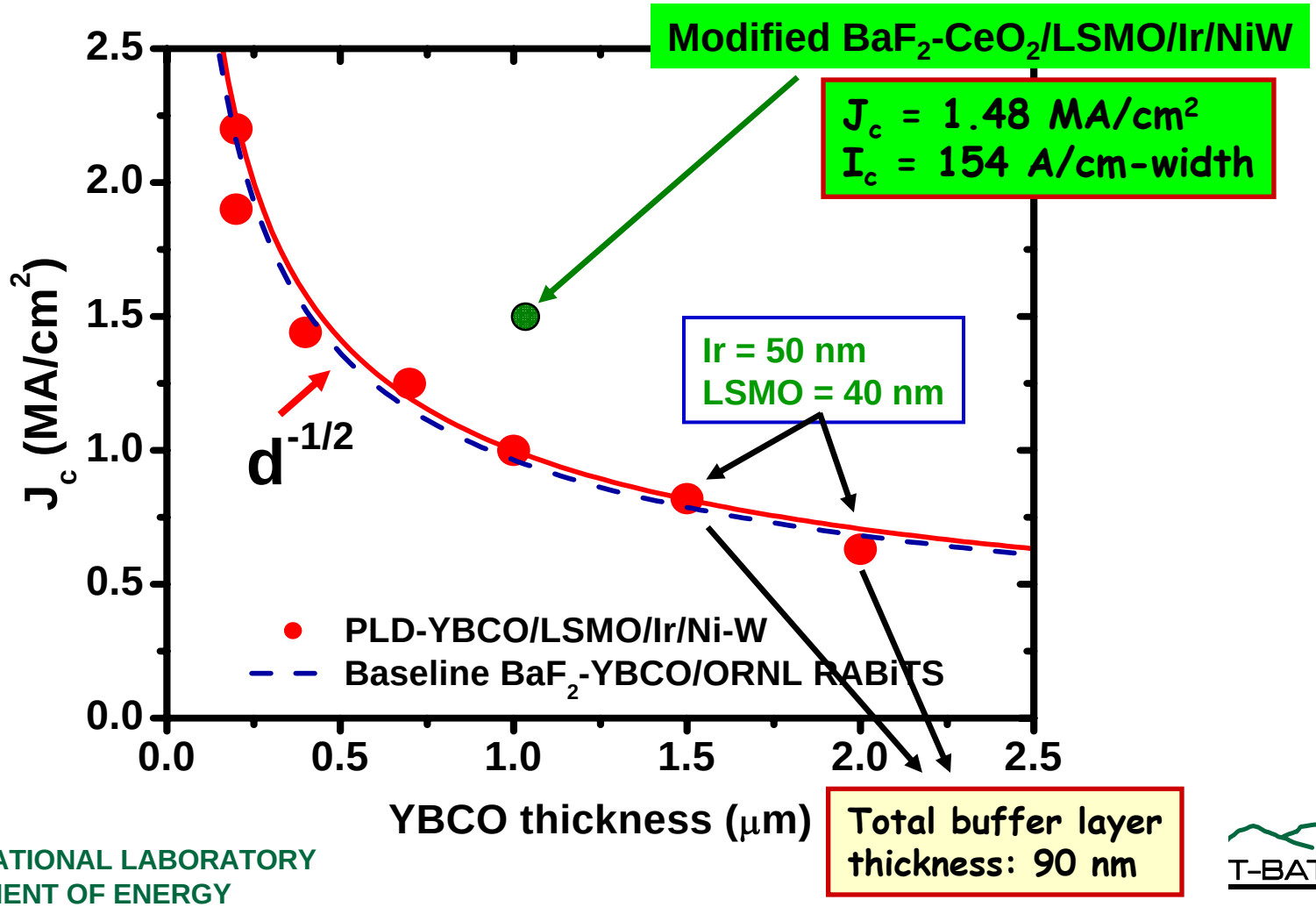
$$I_{HTS} = I_{Net} - I_{Ni\text{-}W}$$



Performance of *in-situ* PLD-YBCO/LSMO/Ir/Ni(W) compares well with baseline-process *ex-situ* BaF_2-YBCO/RABiTS

Similar J_c-d dependence for *ex-situ* & *in-situ* YBCO coatings

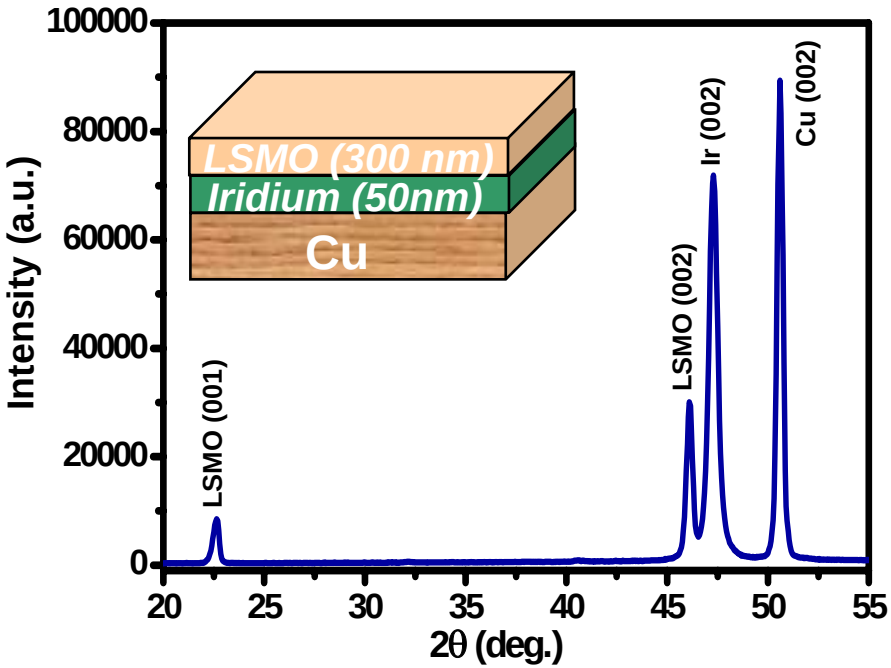
Same J_c performance provided by thinner Ir/LSMO buffers

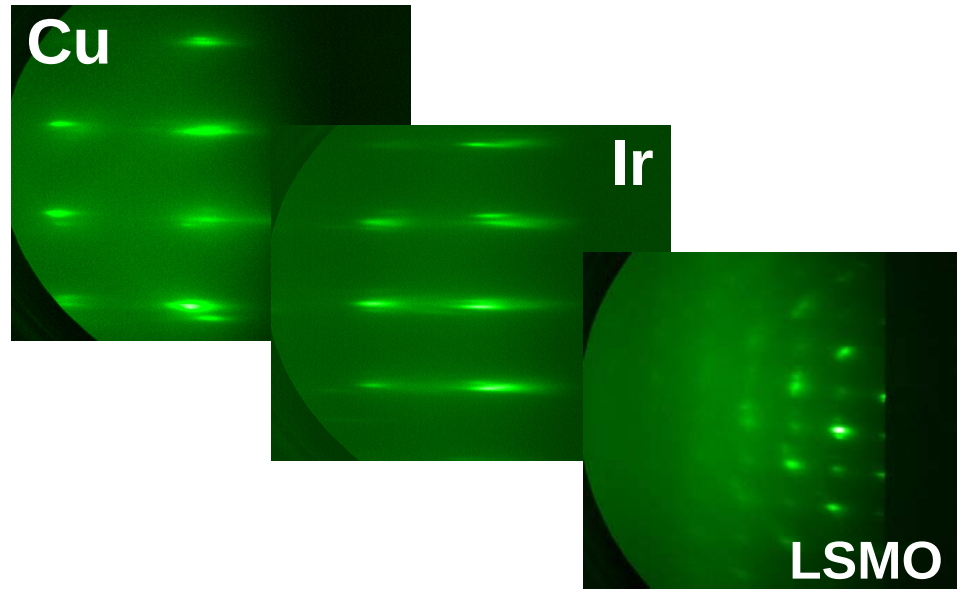


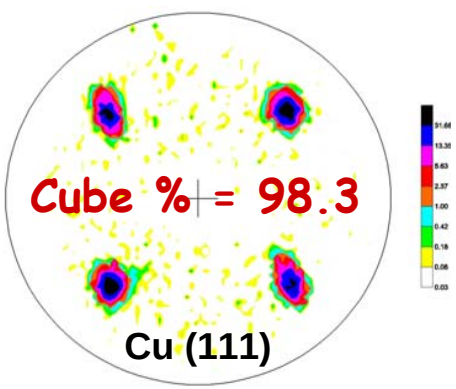
Total buffer layer thickness: 90 nm

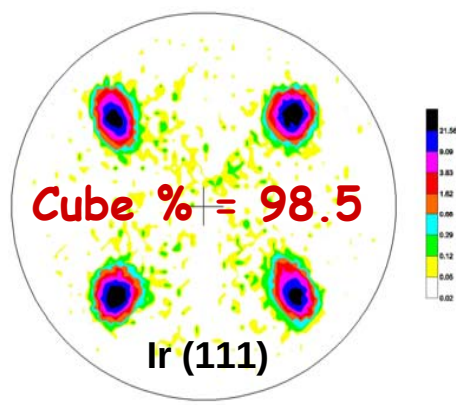
Extension of LSMO/Ir Architecture to Cu-based RABiTS

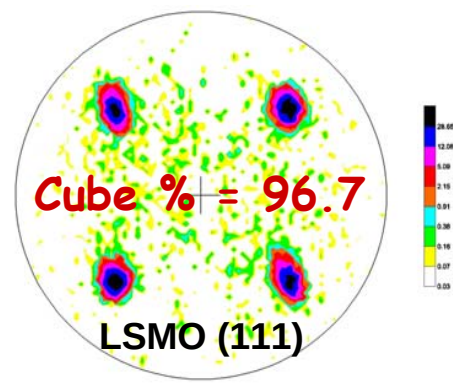
All Layers are epitaxial, cube-on-cube oriented & clean





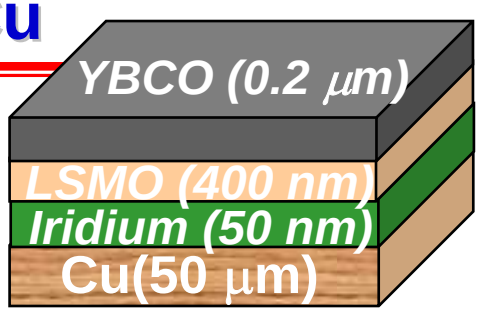


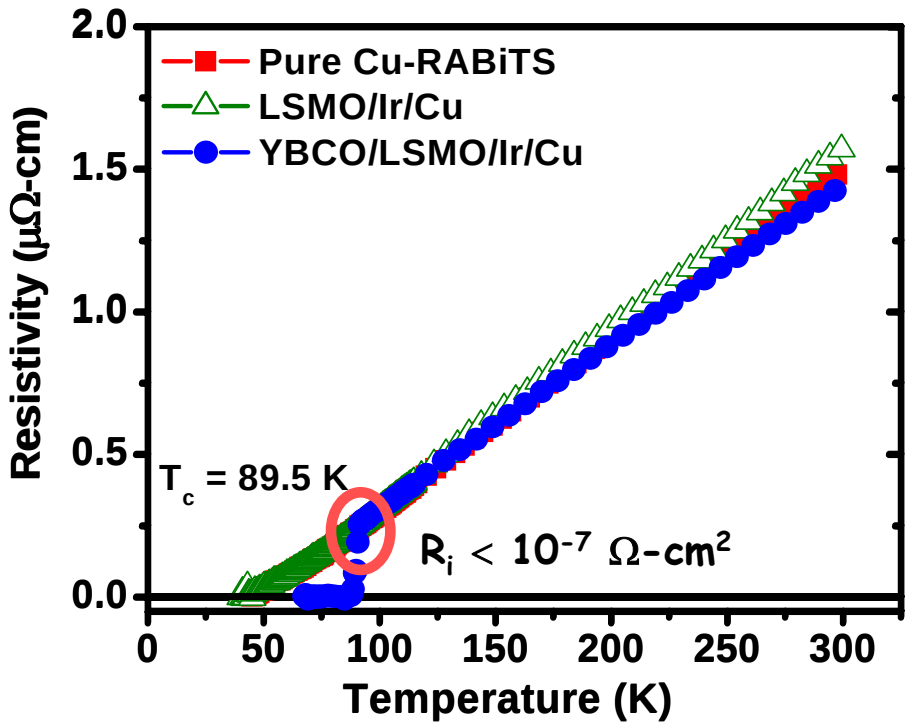


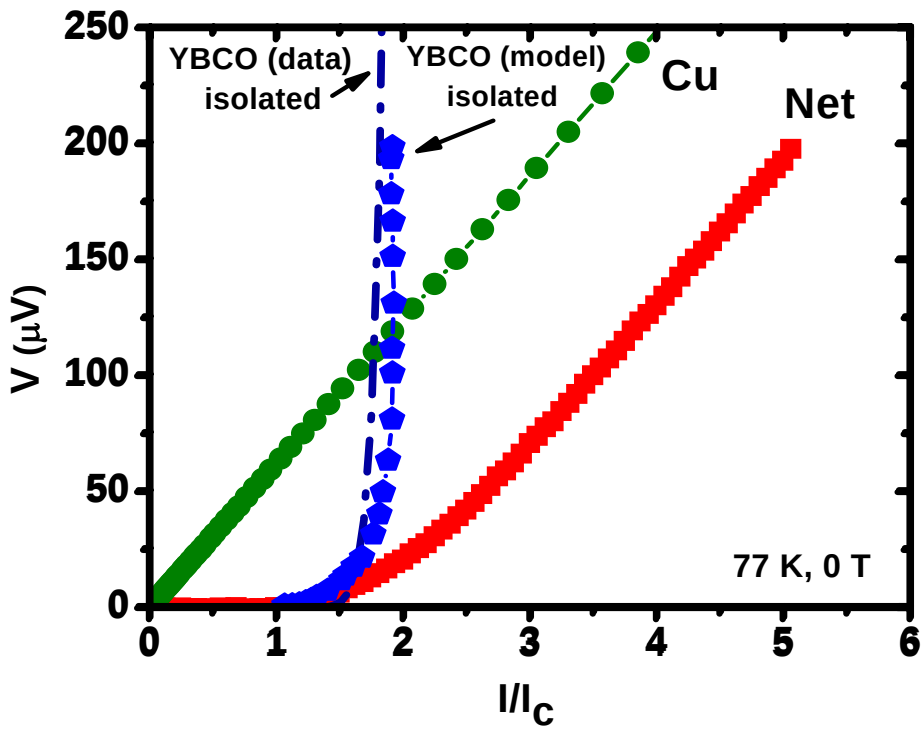


PLD-YBCO(0.2 μm)/LSMO/Ir/Cu: A Fully Conductive Architecture is Obtained on Cu

ρ_{net} - T & I- V shows good electrical coupling among the individual layers



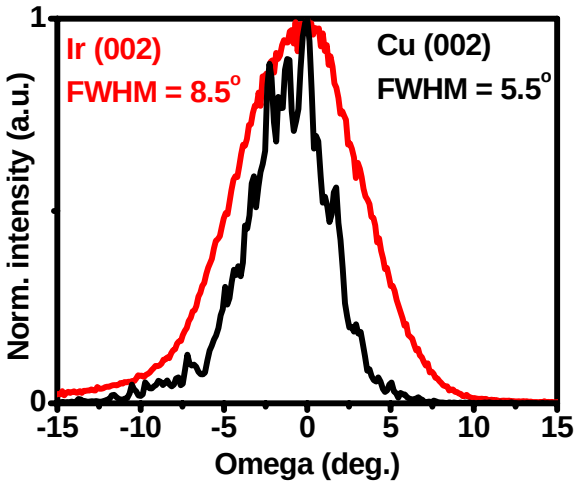


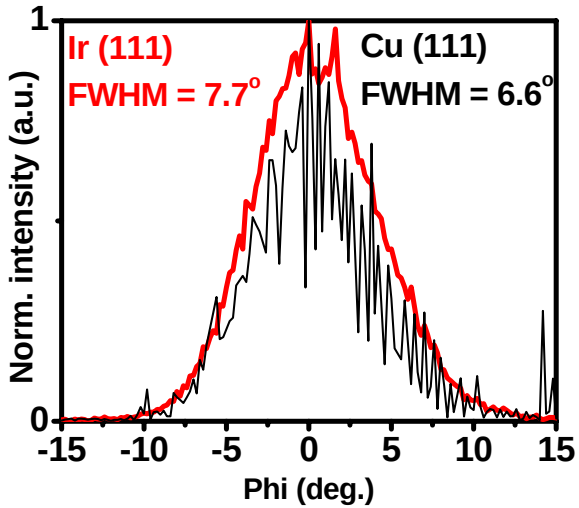


J_c(77K, 0T) ~ 1 x 10^6 A/cm^2

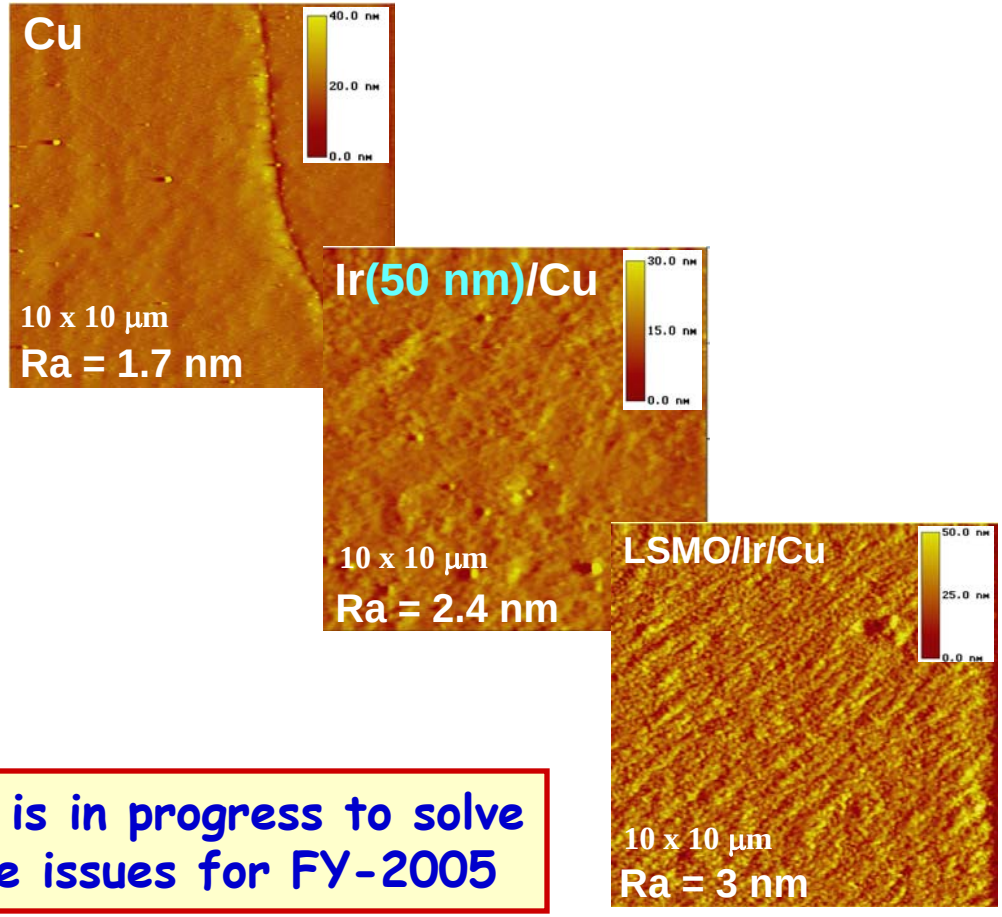
Non optimum J_c performance of YBCO/LSMO/Ir/Cu is likely due to degradation in Ir texture and substrate surface roughness

Ir texture degrades on Cu due to low T= 300 °C deposition





Surface roughness also increases



Work is in progress to solve these issues for FY-2005

Summary

- Developed a multifunctional conductive buffer layer architecture of $La_{0.7}Sr_{0.3}MnO_3/Ir$ on Ni-3at.%W & Cu substrates
  - A good oxygen diffusion barrier
  - A good metal cation diffusion barrier
  - Chemically stable
  - Non-magnetic
- YBCO films on LSMO/Ir/Ni-W & LSMO/Ir/Cu revealed excellent electrical coupling to the underlying substrate
- J_c (0.2 μm) = 2.2 x 10^6 A/cm^2 on Ni-W tapes (optimum performance)
- J_c (0.2 μm) ~ 1 x 10^6 A/cm^2 on Cu (non-optimum performance)
  - Further optimization of buffer structural properties are needed

Presentation Outline

- FY 2004 Results

  Solution-based buffer layers (Watson)

  Development of all conducting buffer layers (Tolga)

  Incorporation of pinning centers in YBCO films on RABiTS (Amit)

  Status of Cu-based substrates (Amit)

- FY 2004 Performance and FY 2005 Plans (Amit)

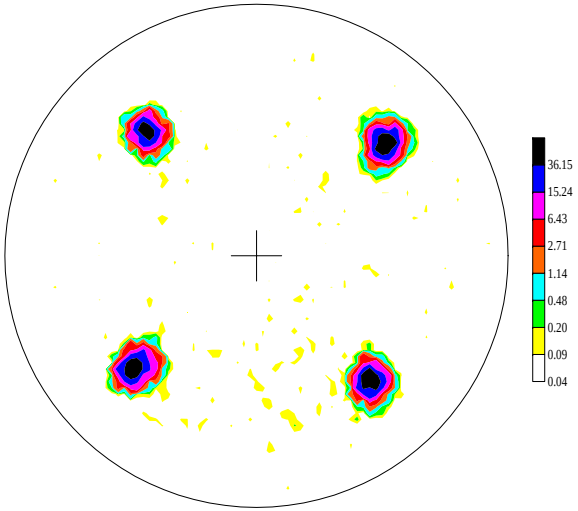
- Research Integration

Development of Cu-based substrates

Long lengths of sharply textured Cu substrates were fabricated in FY04

1 km of 1 cm wide Cu substrate fabricated

Cu(111) log-scale pole figure
~100% cube



FWHM $\Delta\phi$ = 4.0 (True Phi)
FWHM $\Delta\omega$ = 6.9, 5.2

Development of Cu-alloy substrates

<u>Goal</u>: High strength, high conductivity, cube-textured alloy substrate with at least a yield strength of 100-150MPa and 50% IACS conductivity

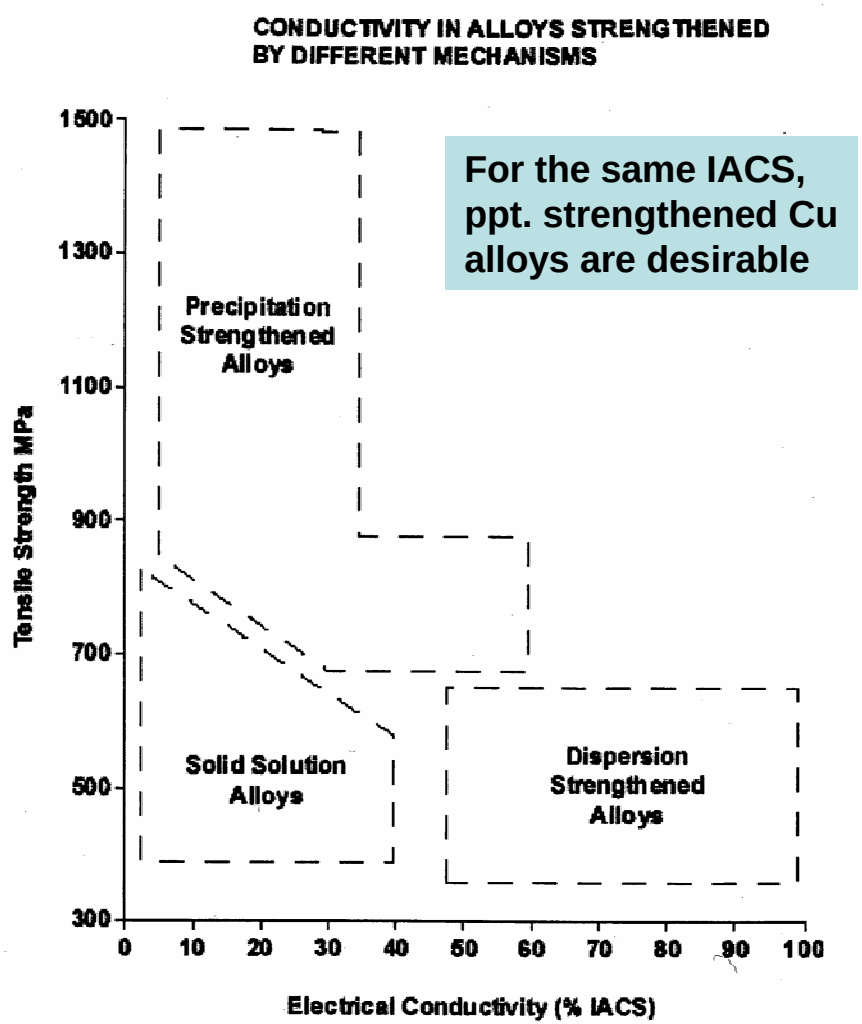
Cube texture formation in Cu is very sensitive to impurity and alloy additions.

- In solid solution alloys, small amounts of impurities result in complete loss of cube texture: 5wt%Zn, 1wt%Sn, 4wt%Al, 0.5wt%Be, 0.5wt%Cd, 0.0025at%P, 0.3at%Sb, 1.5at%Mg, 4.2at%Ni, 0.18at%Cd, 0.047at%As
- Small amounts of oxygen result in complete loss of cube texture
- Most commercial alloys of Cu are not made using OFHC Cu and hence are not suitable

Commercially available grades of oxide ***dispersion strengthened***, OFHC, Cu, which is both strong and conductive, containing 0.15-0.6wt%Al_2O_3 particles stabilize the as-rolled texture and prevent full recrystallization.

OFHC Cu-Nb multifilamentary composites which also have high strength and conductivity have technical problems:
-Delamination at Cu/Nb interface during rolling due to limited solid solubility

Development of Cu-alloy substrates



For the same IACS, ppt. strengthened Cu alloys are desirable

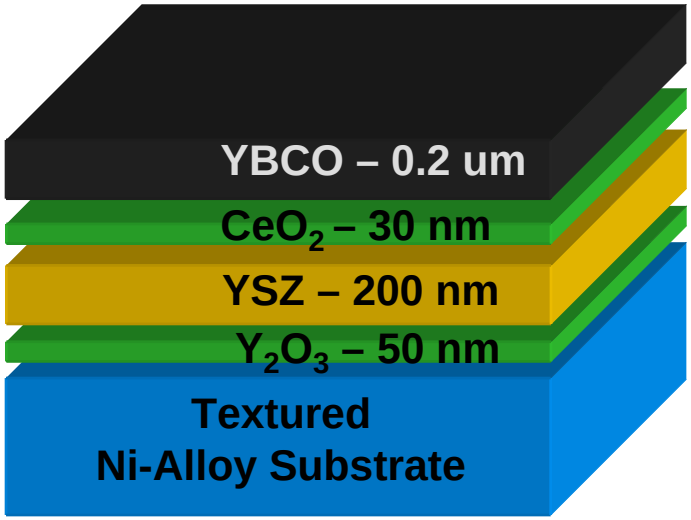
Directions for future Work:

- Work with precipitation strengthened alloys: achieve cube texture first then form precipitates for strengthening & re-gain conductivity
- Composites such as powder-in-tube type approach.
  - ORNL's US patent No.:6,180,570
- Laminating textured pure Cu to strengthened and conductive but un-textured Cu-alloy.
  - ORNL's US patent No.:6,375,768
- Forming a 45°-rotated cube texture in as-rolled strengthened & conductive Cu-alloy.
  - ORNL's US patent No.:6,740,421

Level of effort will depend on available funding

Enhanced flux-pinning in YBCO films on RABiTS via microstructural modifications

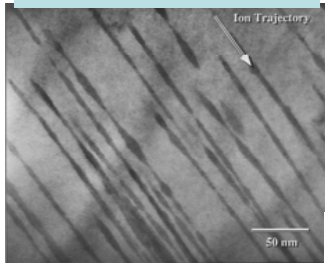
Experimental details



- AMSC RABiTS substrate used in this study
- YBCO deposited using PLD
  - XeCl(308nm) excimer laser Model LPX 305
  - Rep. Rate: 10-20 Hz
  - Subs. Temp. = 790°C
  - PO_2 = 120 mTorr
- All work on RABiTS substrates

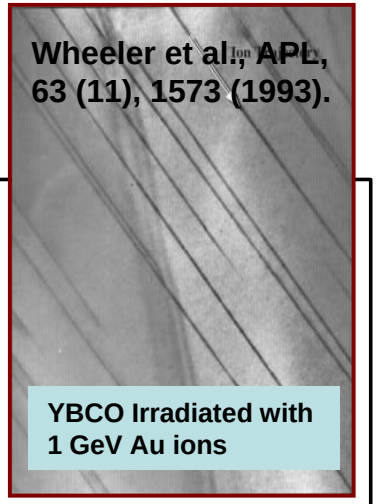
Motivation: Linear defects by heavy ion irradiation

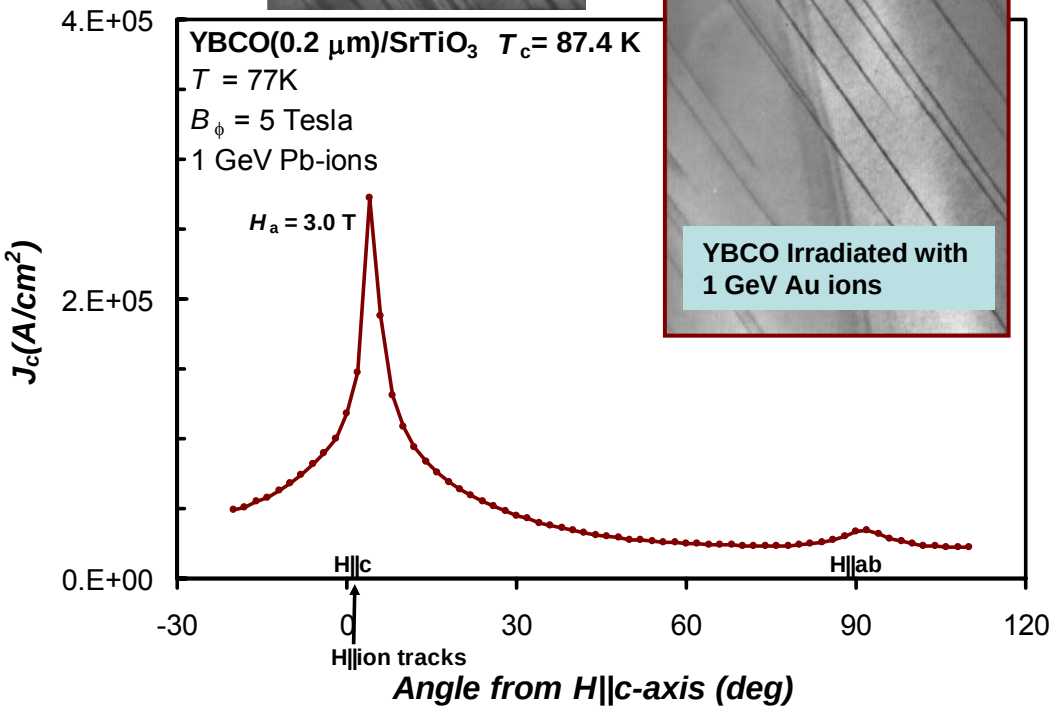
YBCO Irradiated with 580 MeV Sn ions



Civale et al., Phys. Rev. Lett. 67 (5): 648-651, 1991.

Wheeler et al., APL, 63 (11), 1573 (1993).

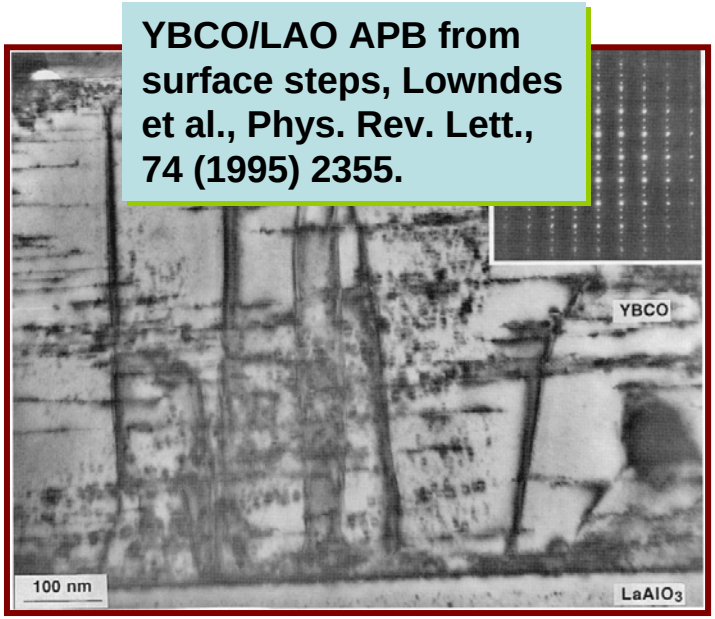


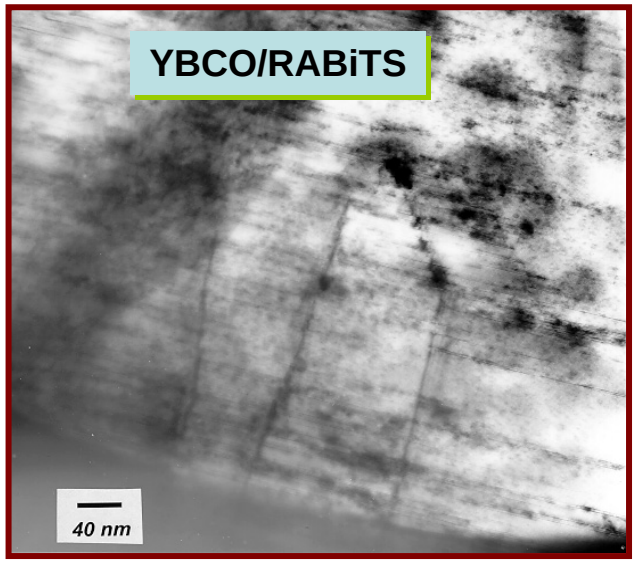


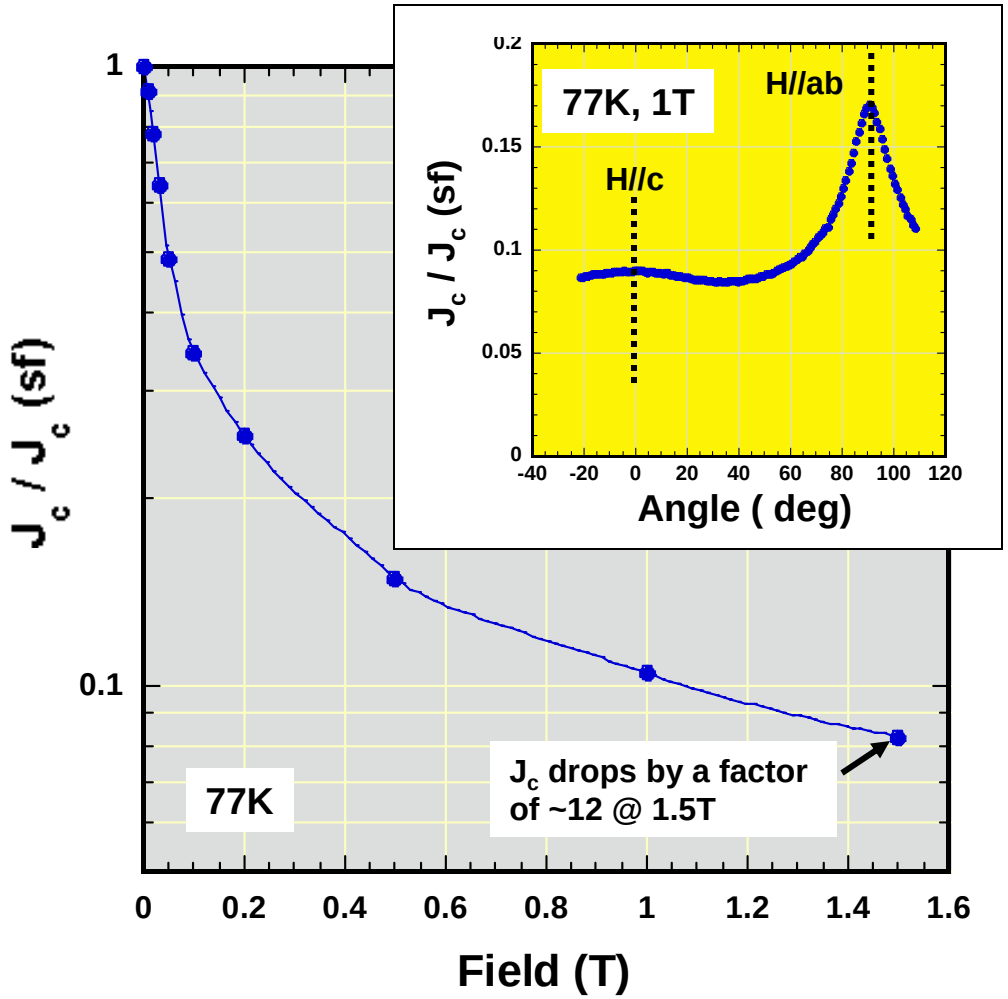
Christen et al., ORNL

UT-BATTELLE

Natural defects in films and coated conductors







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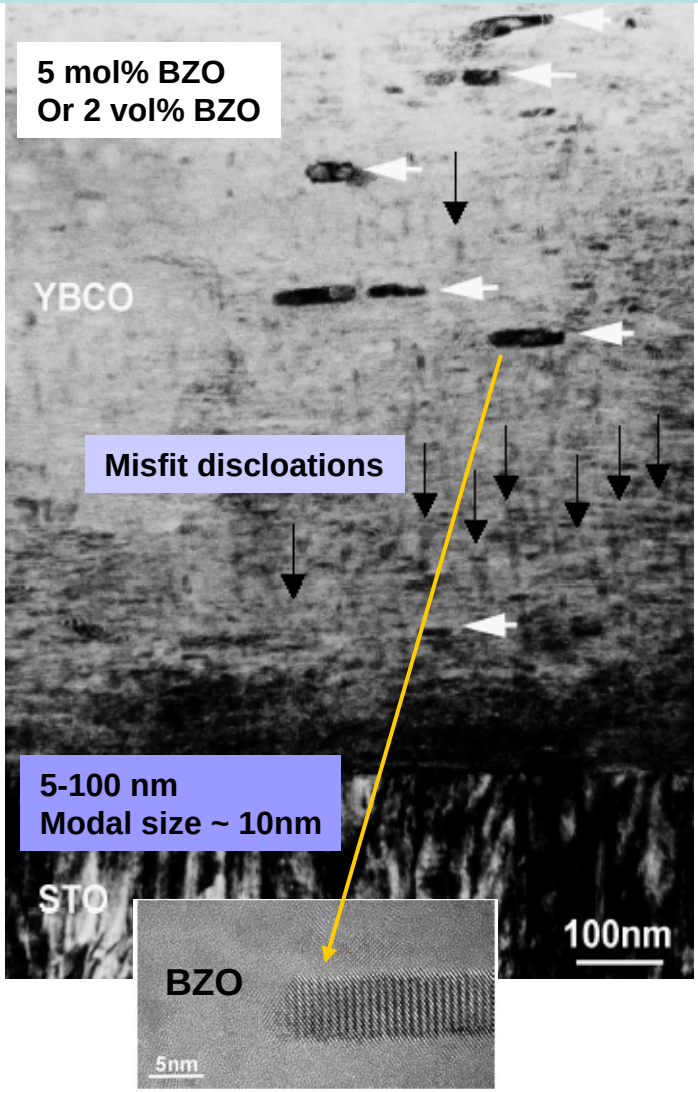
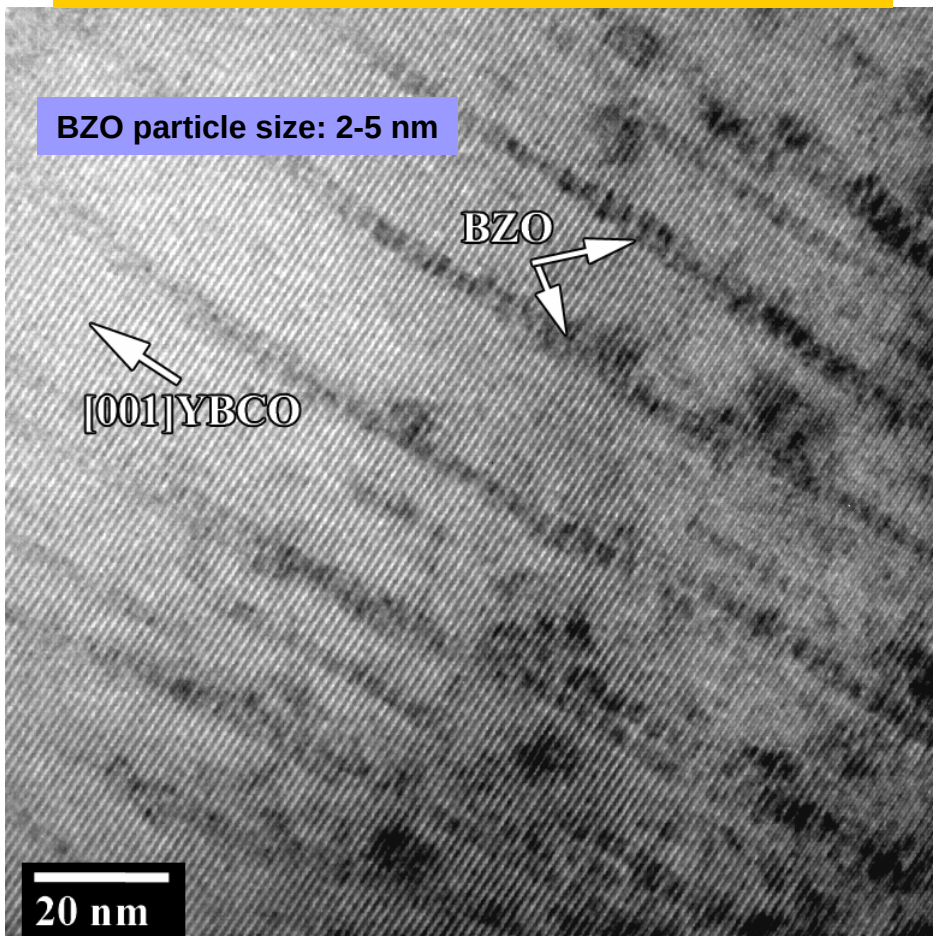
Enhanced flux-pinning in coated conductors

Driscoll et al., Nature Mat., 3 (2004) 439.



Self-aligned nanodots in YBCO/RABiTS



Massive enhancement in pinning is obtained

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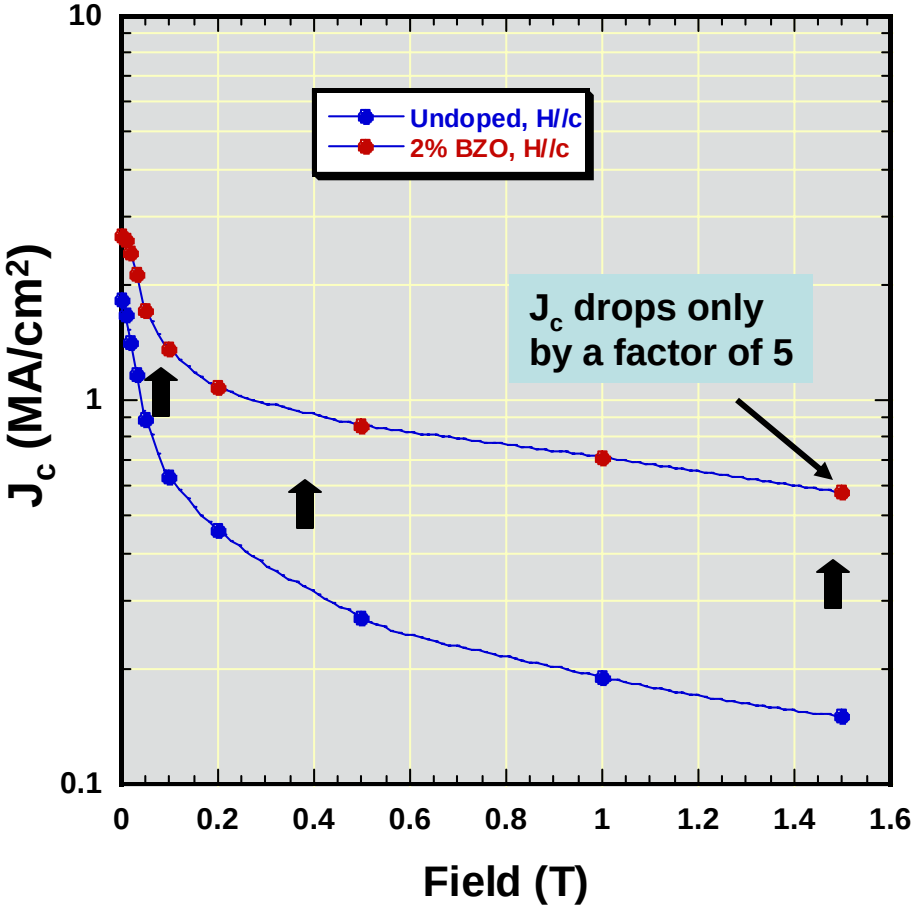
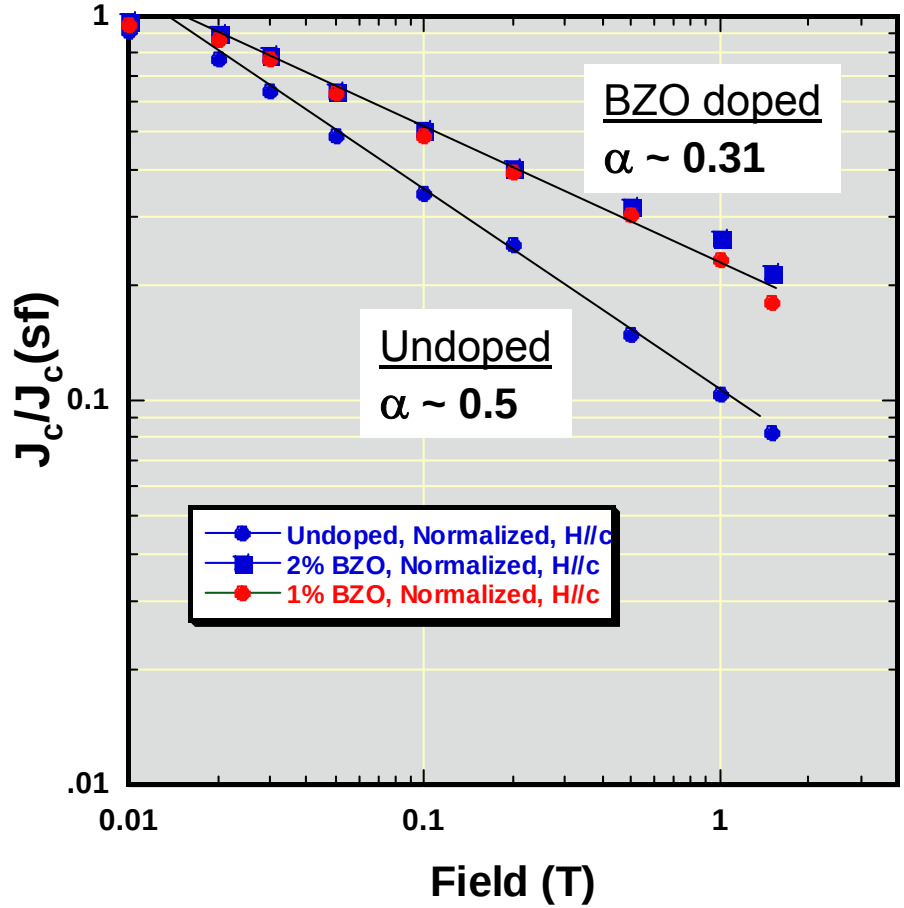
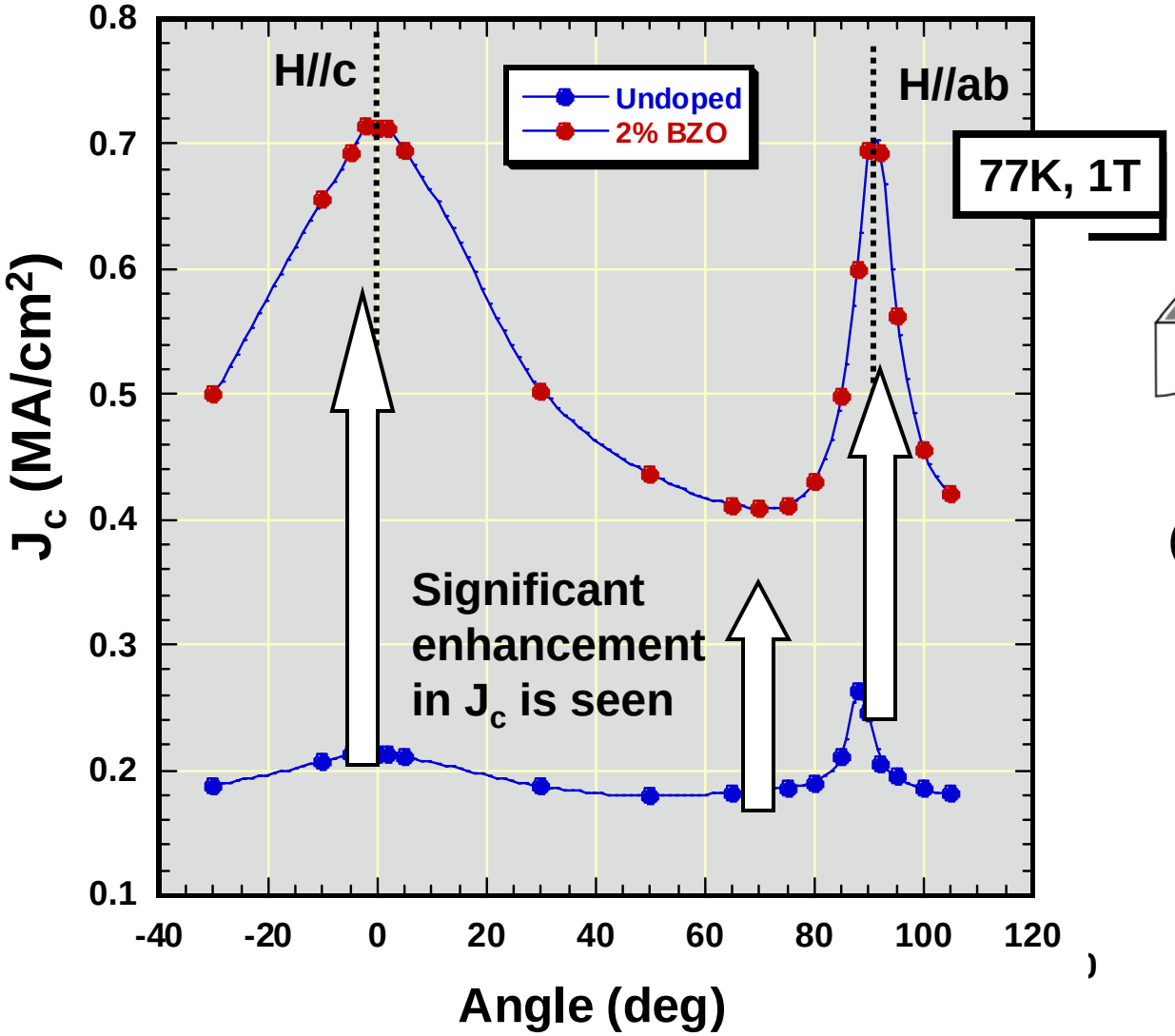
Pinning by self-aligned BZO nano dots & rods: J_c in low fields

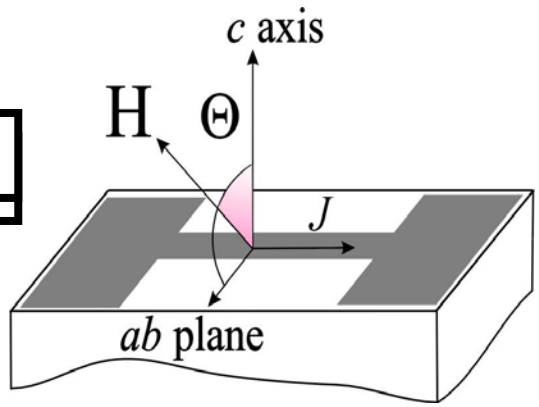


Change in α value for $J_c \sim H^{-\alpha}$



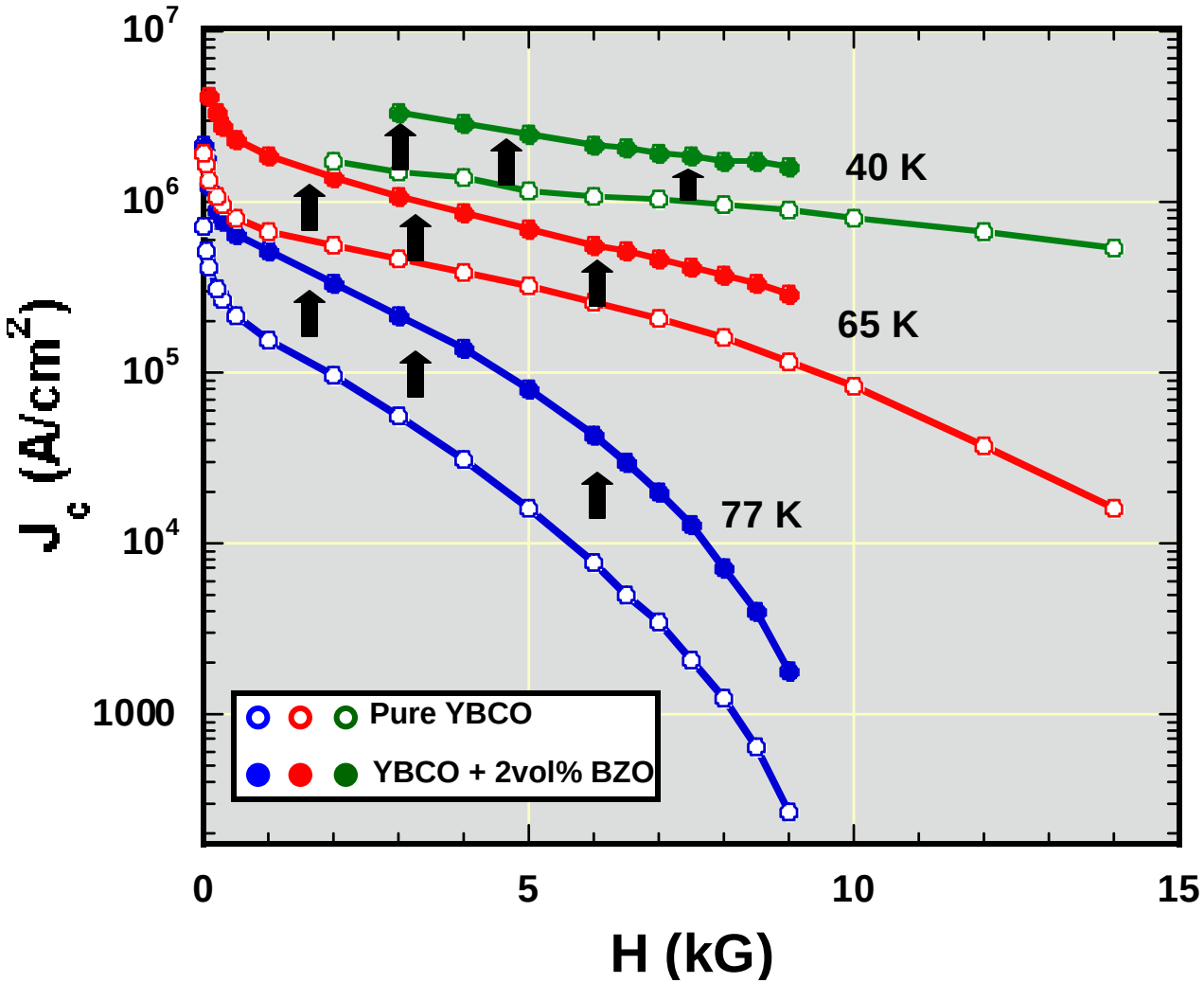
Significant improvement in the angular dependence is obtained for YBCO with self-aligned BZO nanodots & rods





H ⊥ J always
(maximum Lorentz force)

Significant improvement is observed in YBCO + 2vol% BZO in higher fields and lower temperatures



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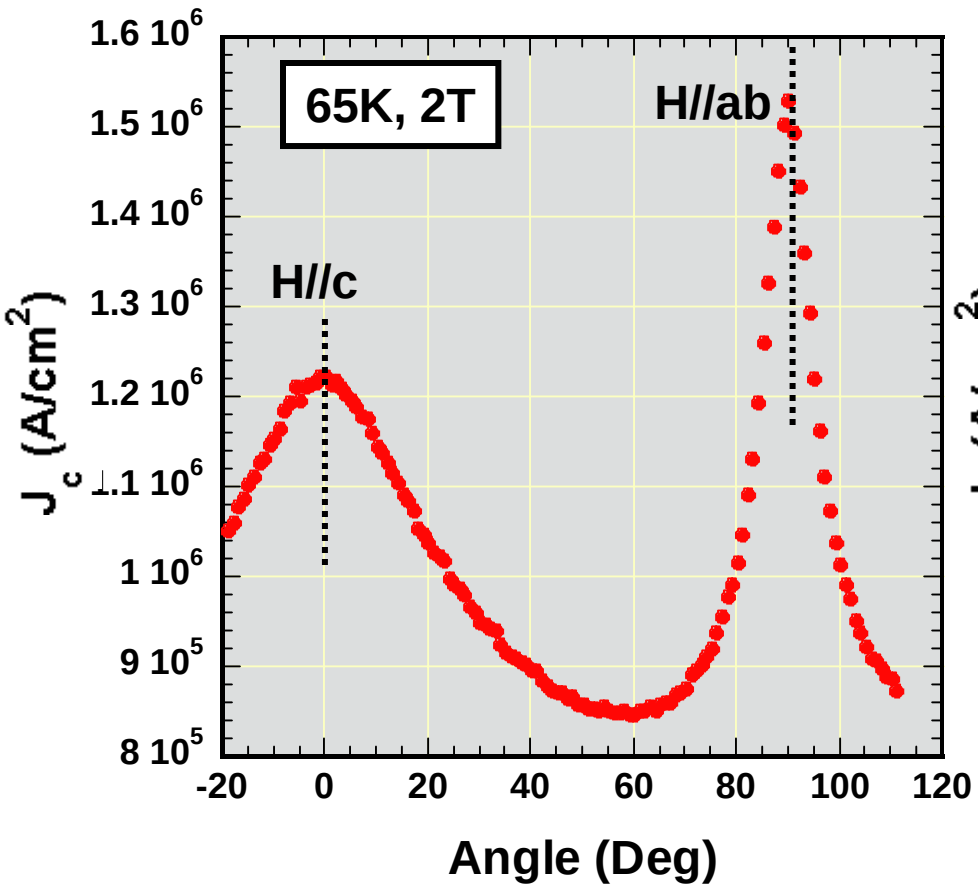
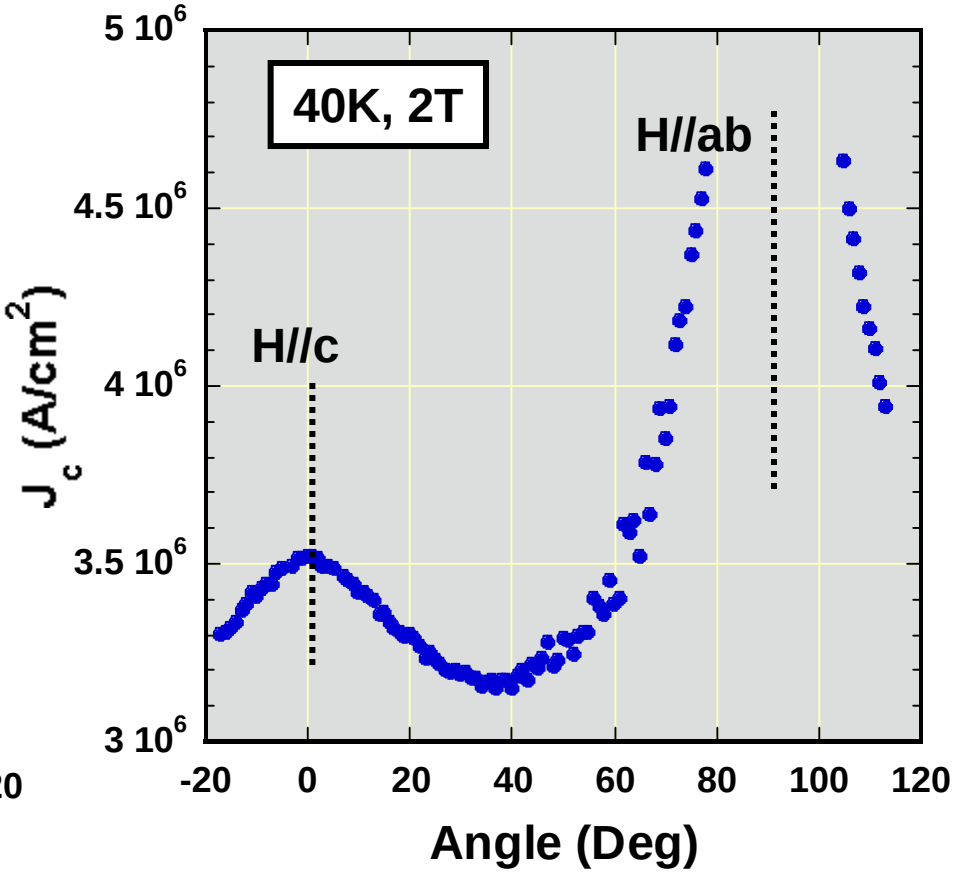
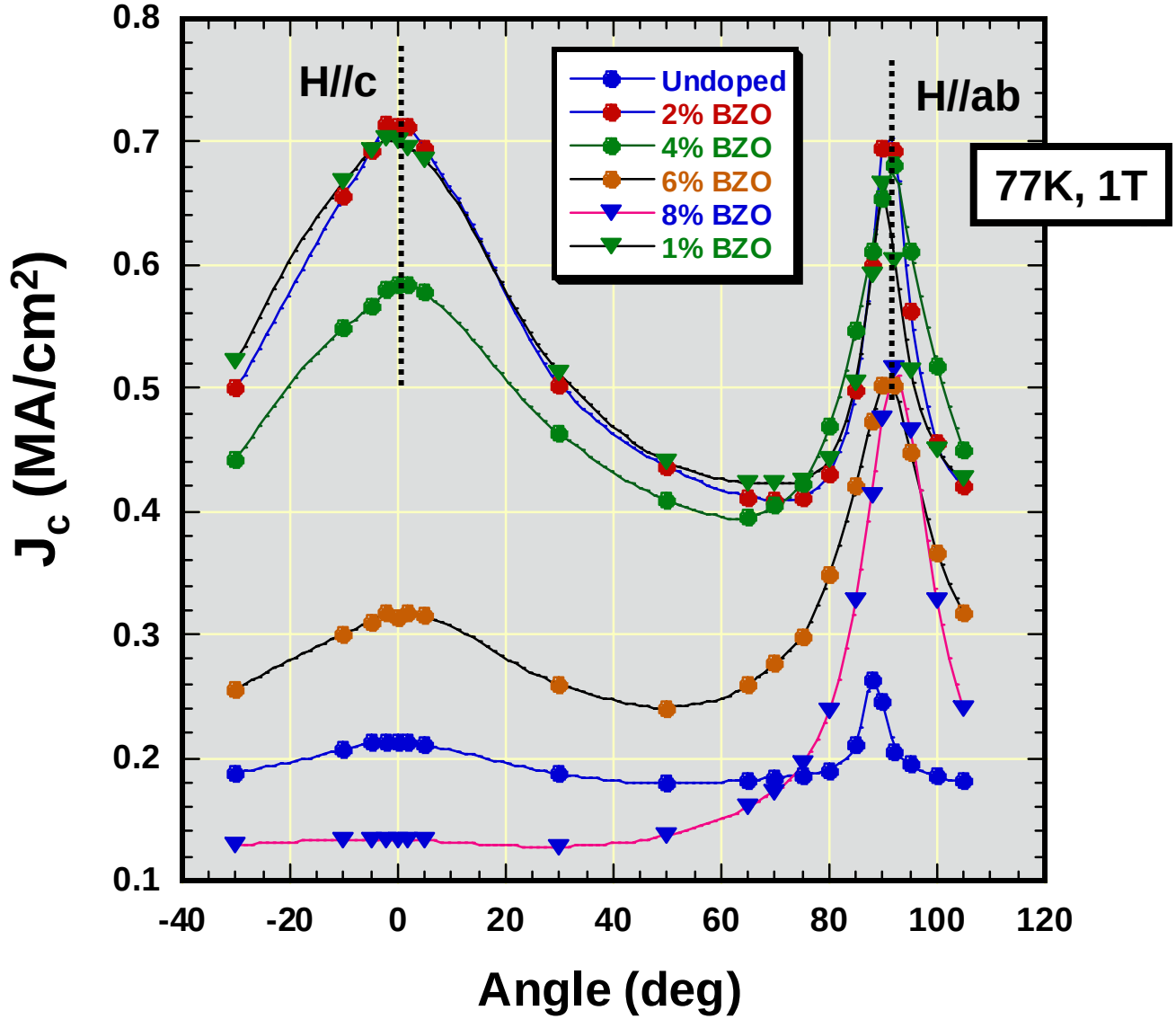
Angular dependence of J_c at lower temperatures for YBCO + 2% BZO

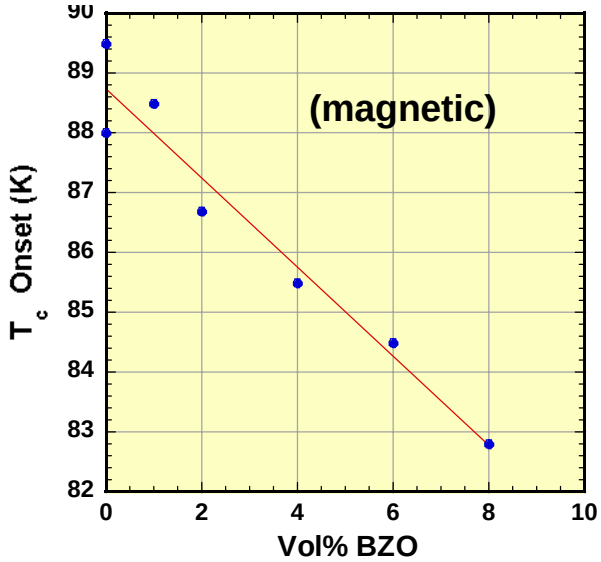


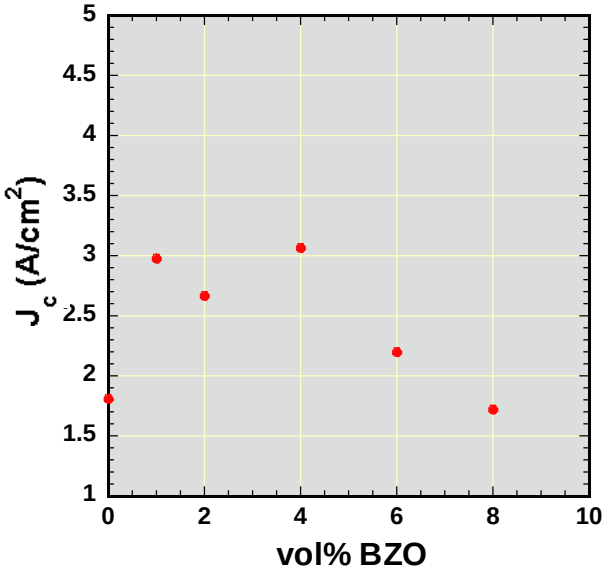


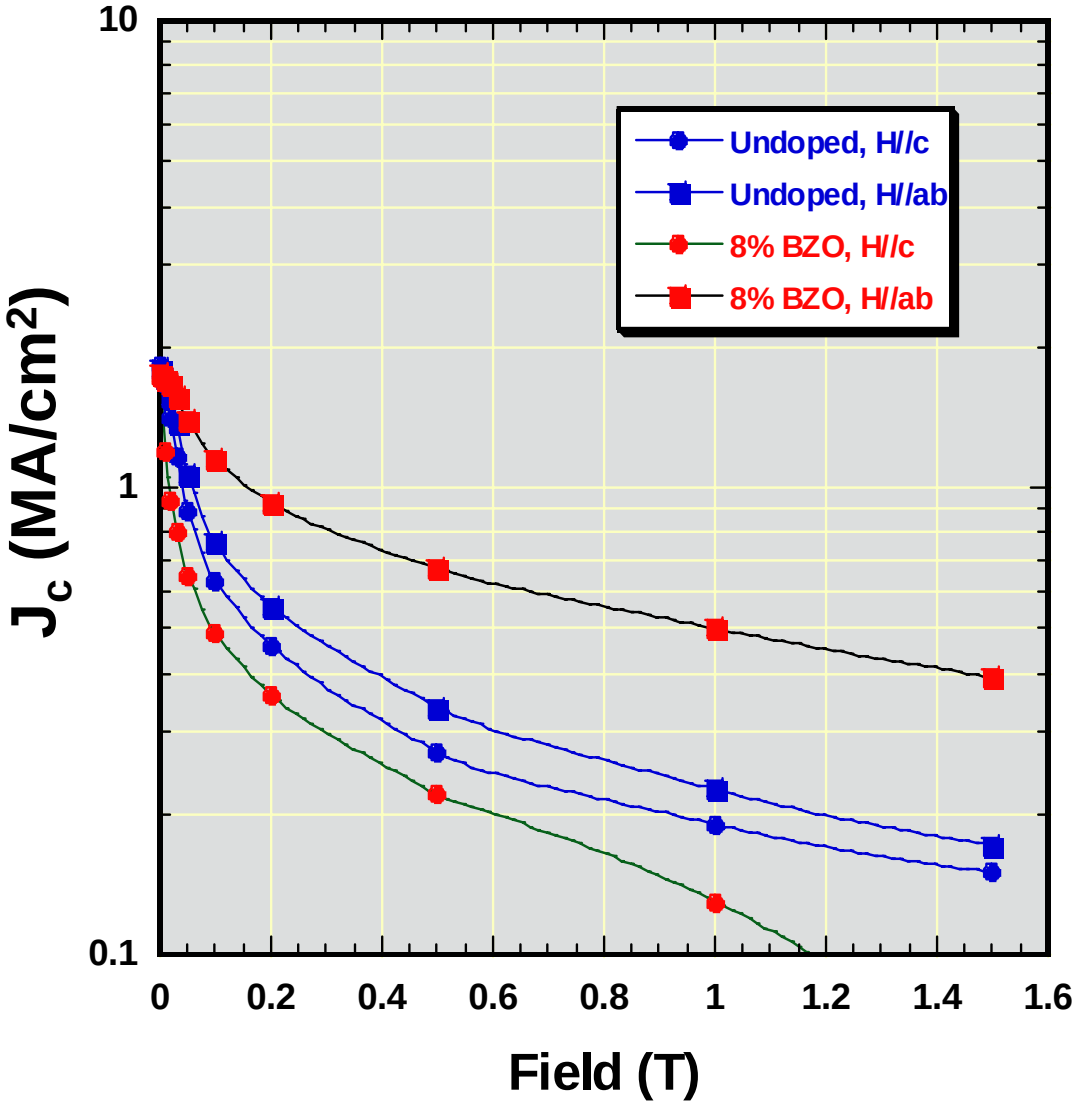
Changes in the angular dependence of J_c with increased volume % of self-aligned BZO nanodots & rods



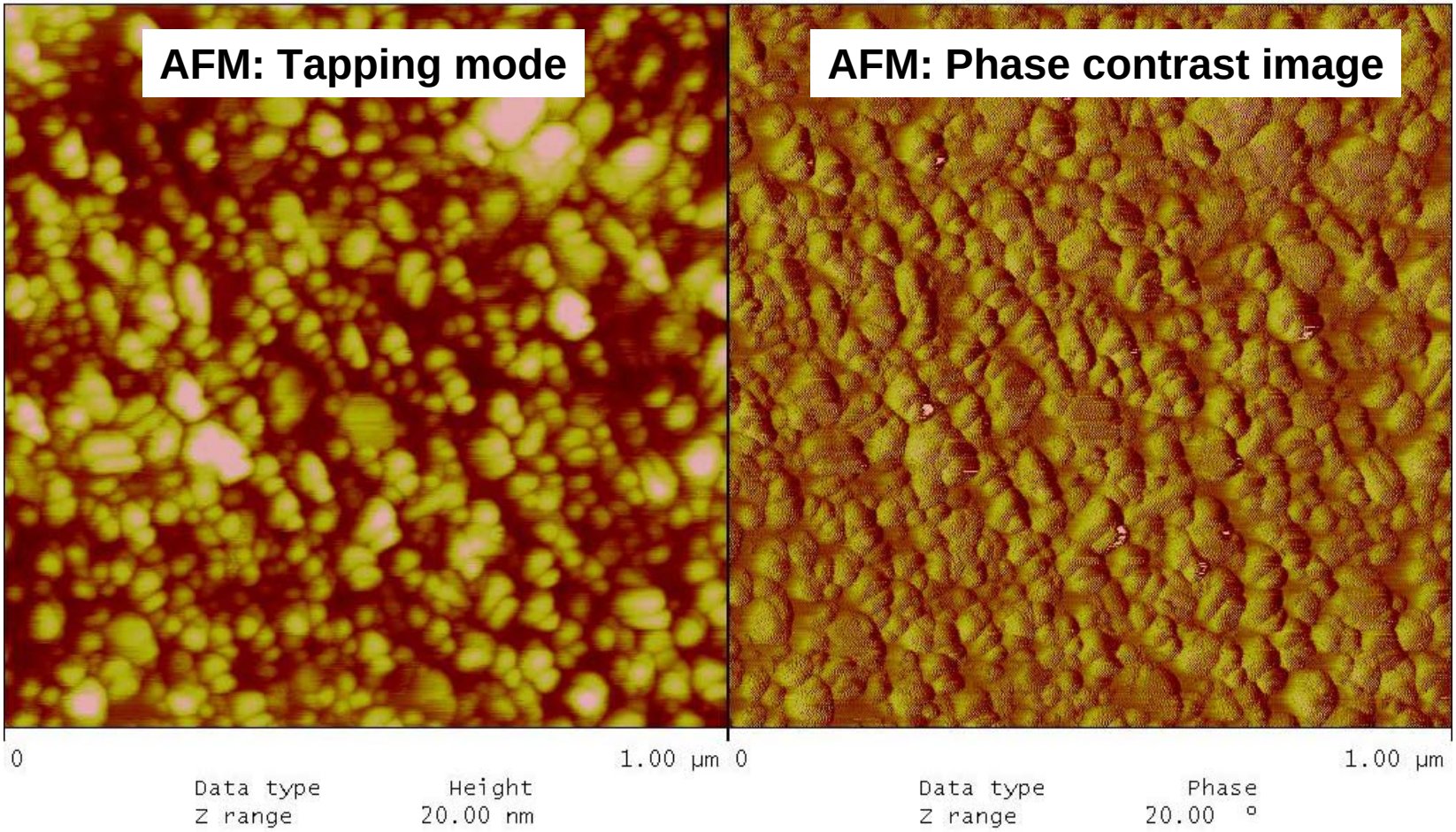
Effect of increasing the defect density by increased volume % of self-aligned BZO nanodots





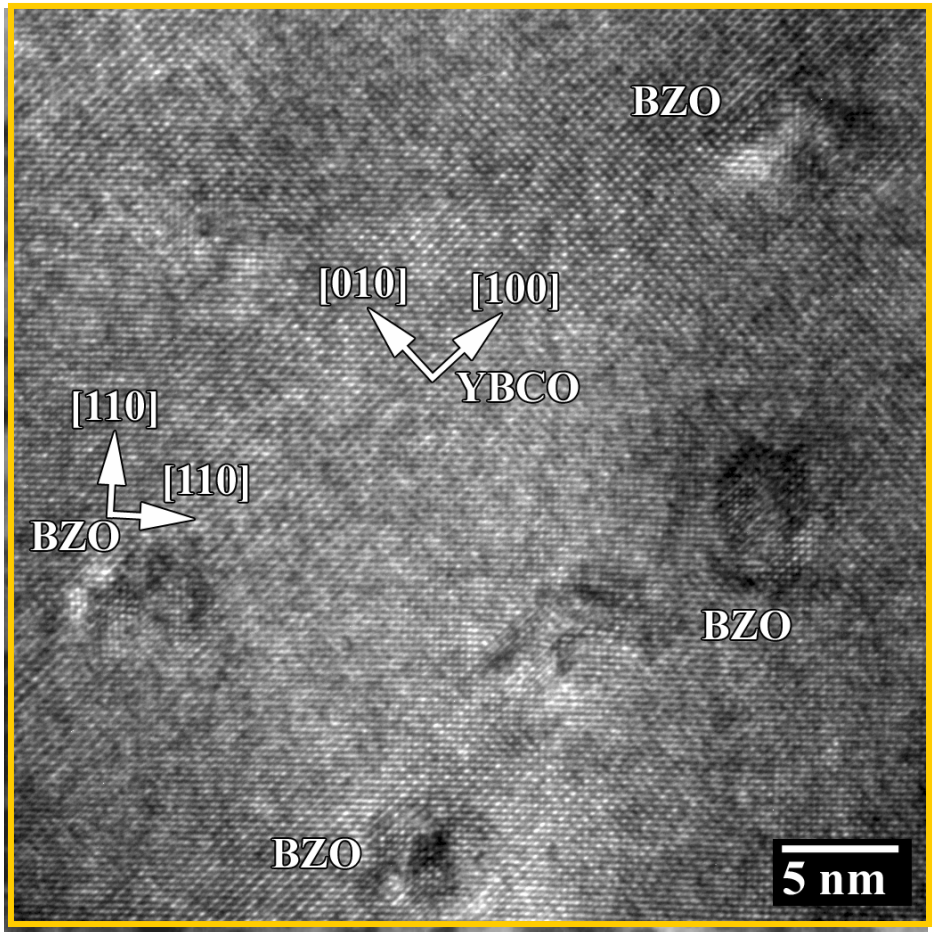


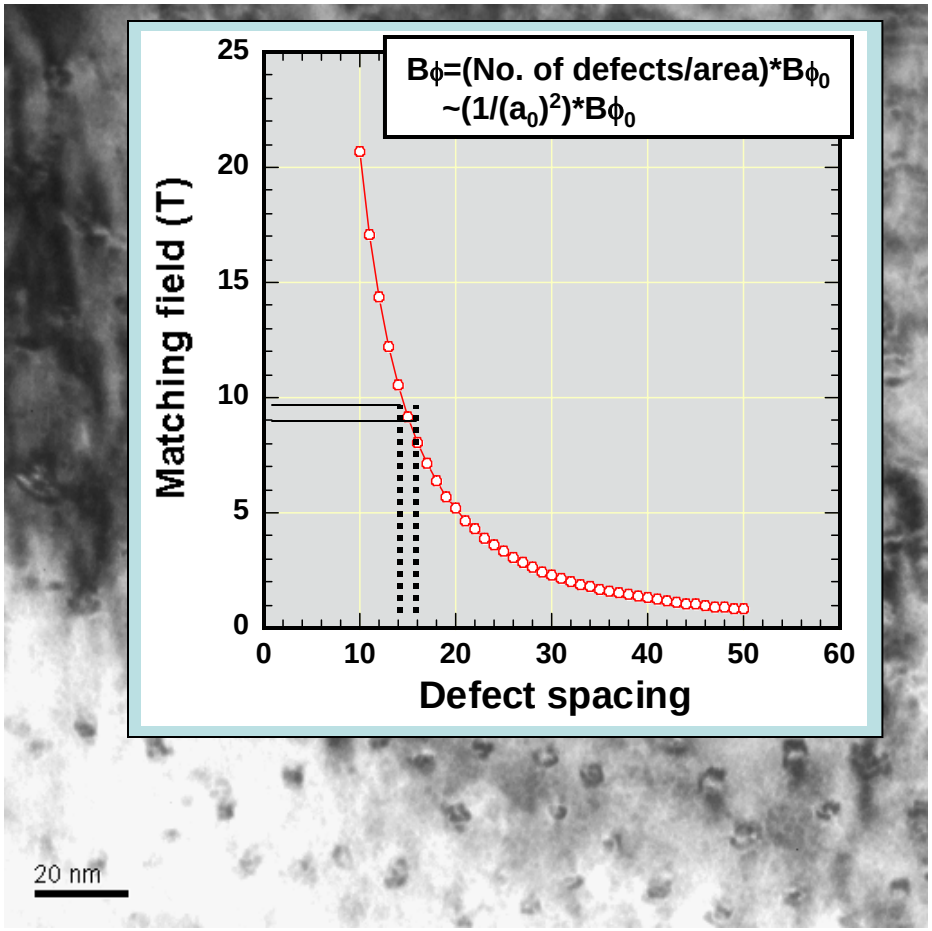
Phase contrast AFM shows no apparent segregation of particles on surface



Phase contrast is determined by differences in elastic constant

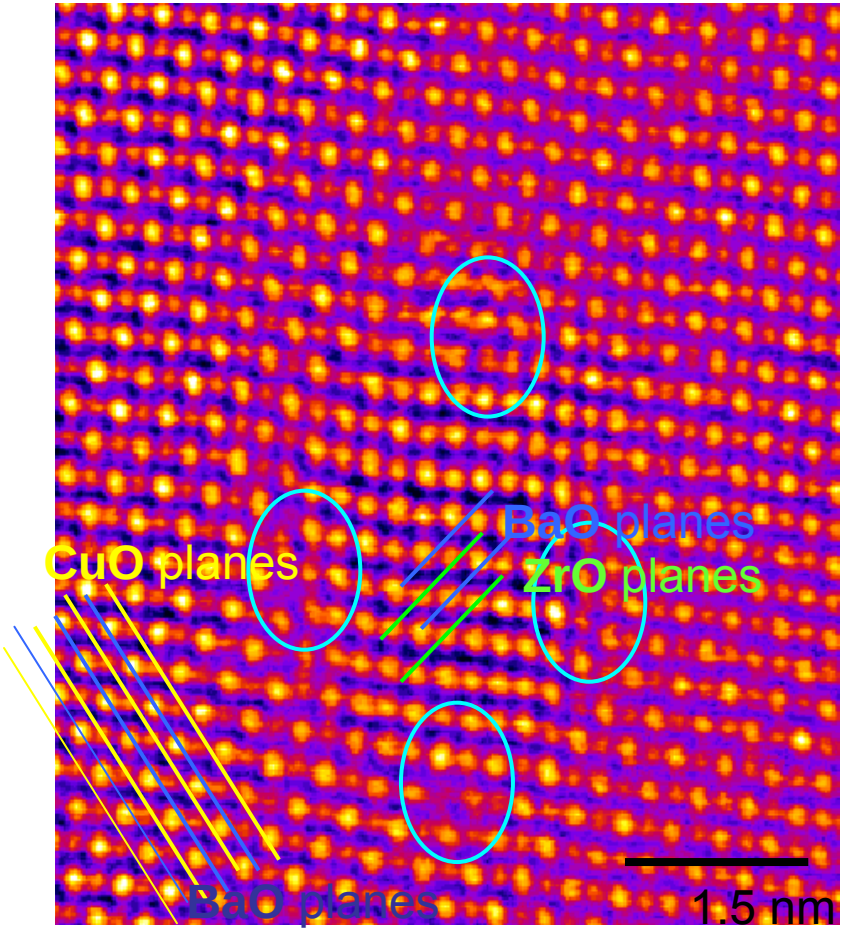
Plan view TEM for 2% BZO-YBCO films showing BZO nanodots/rods

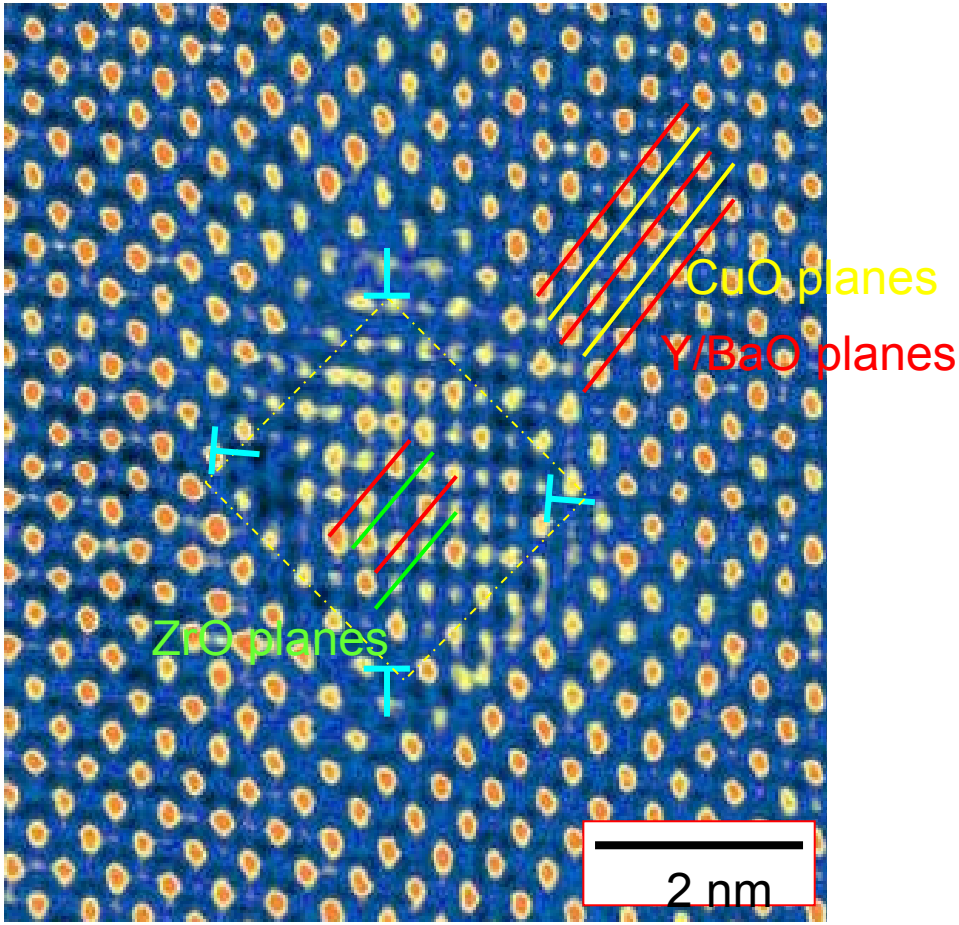




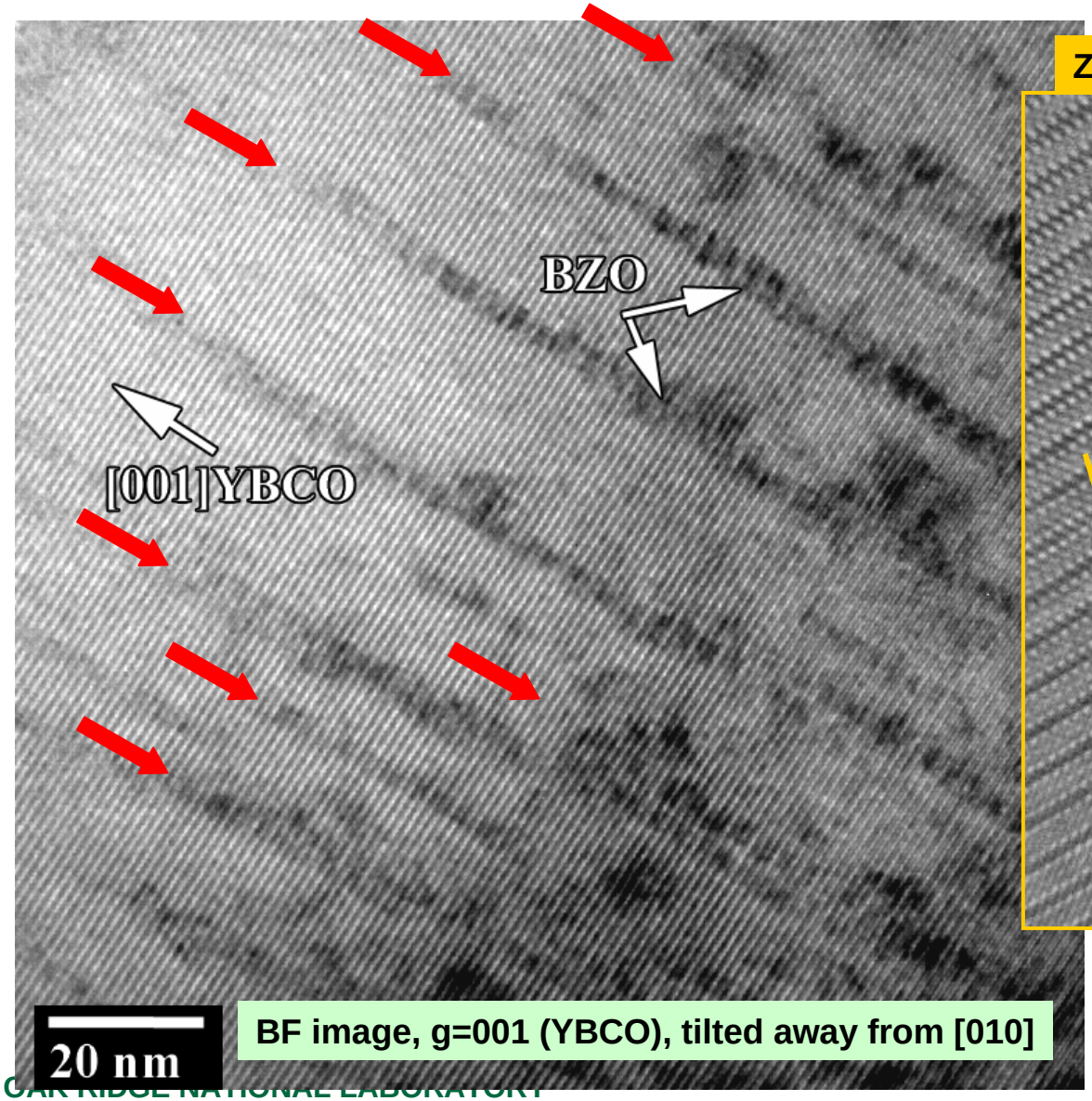
UT-BATTELLE

Z-contrast imaging in plan view confirms BZO nanodots/rods in plan view TEM and shows misfit dislocations



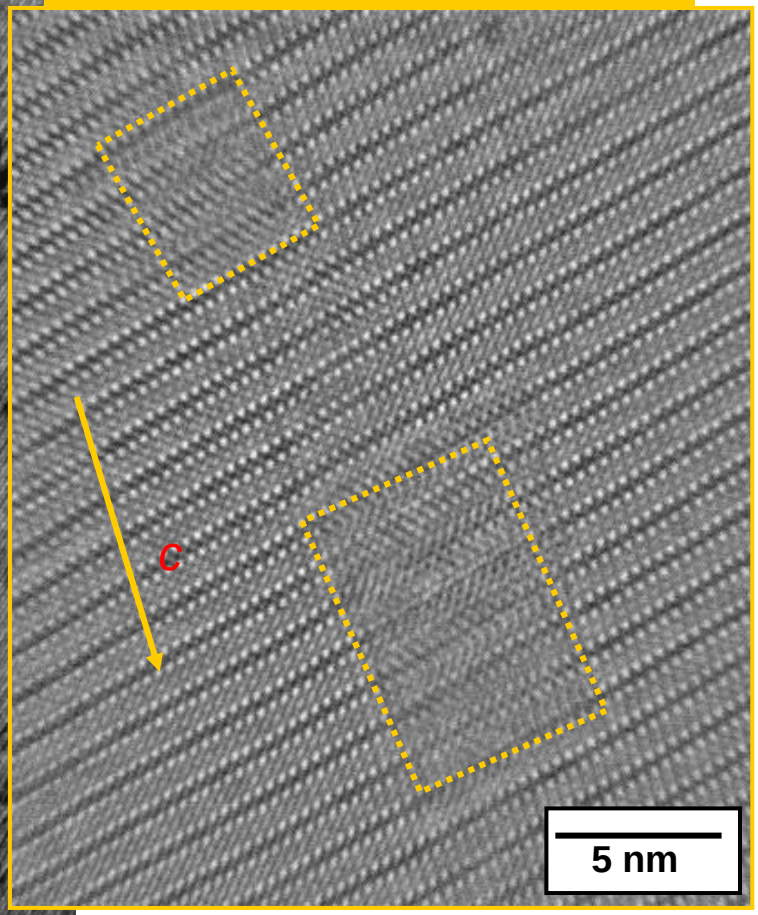


Cross-section TEM shows self-aligned nanodots everywhere in the film. No large particles or disc-like particles observed

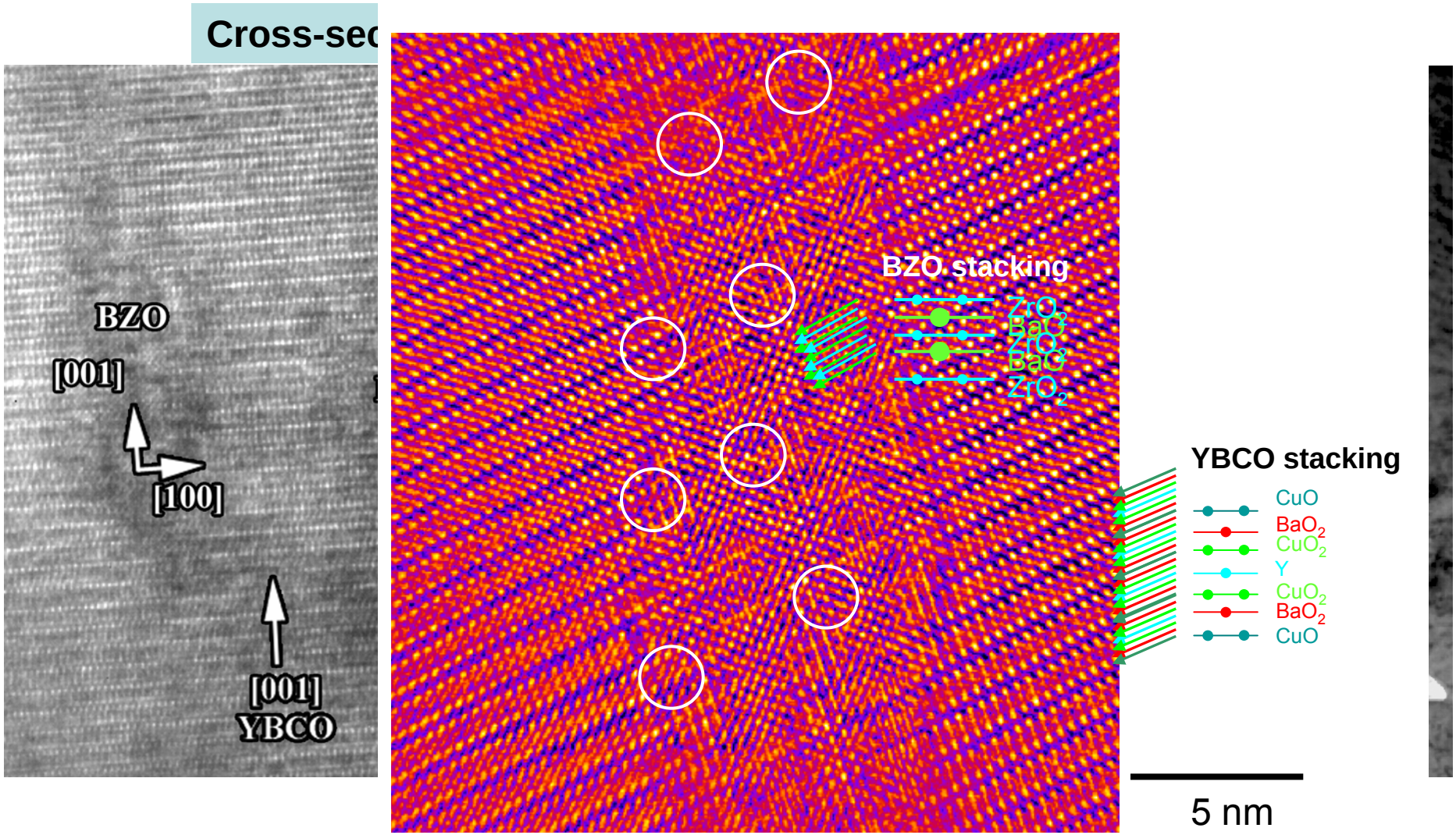


BF image, g=001 (YBCO), tilted away from [010]

Z-contrast image of BZO nanodots

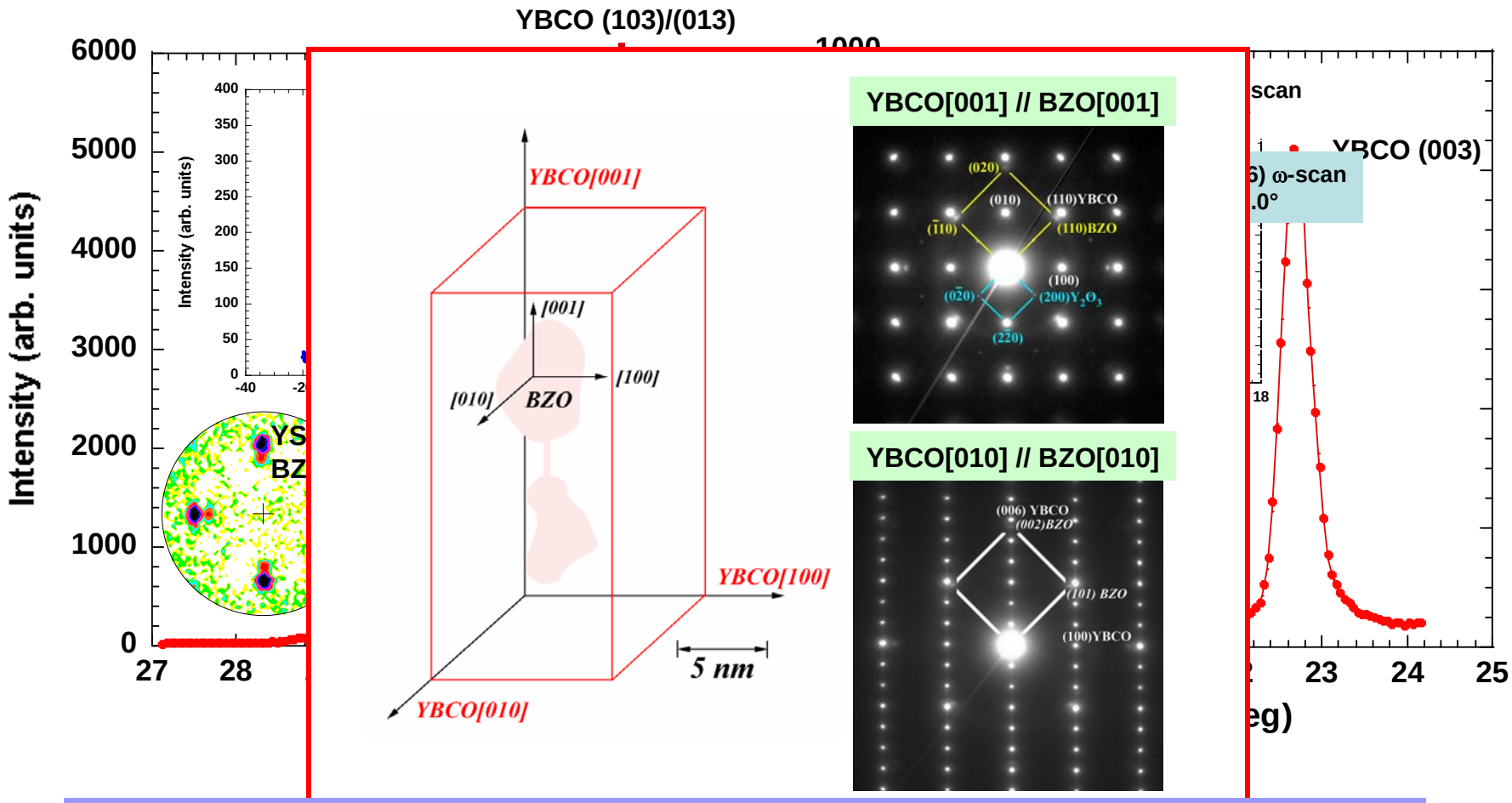


BZO nanorods are also present in the sample



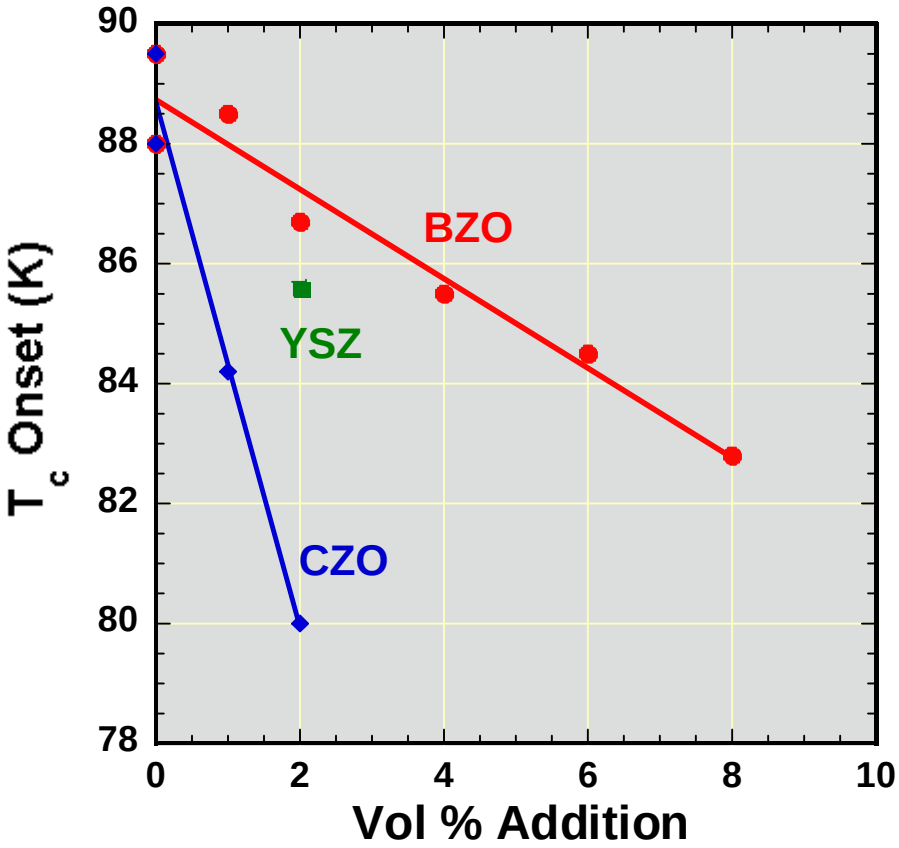
UT-BATTELLE

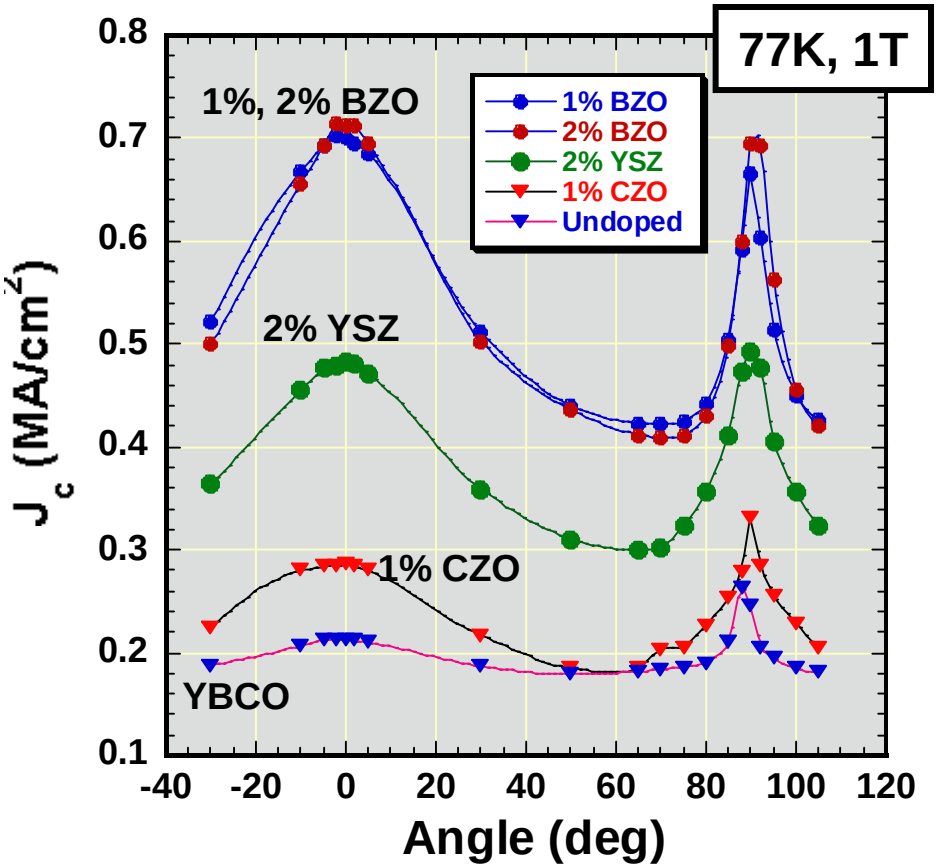
BZO nanodots are epitaxial with YBCO



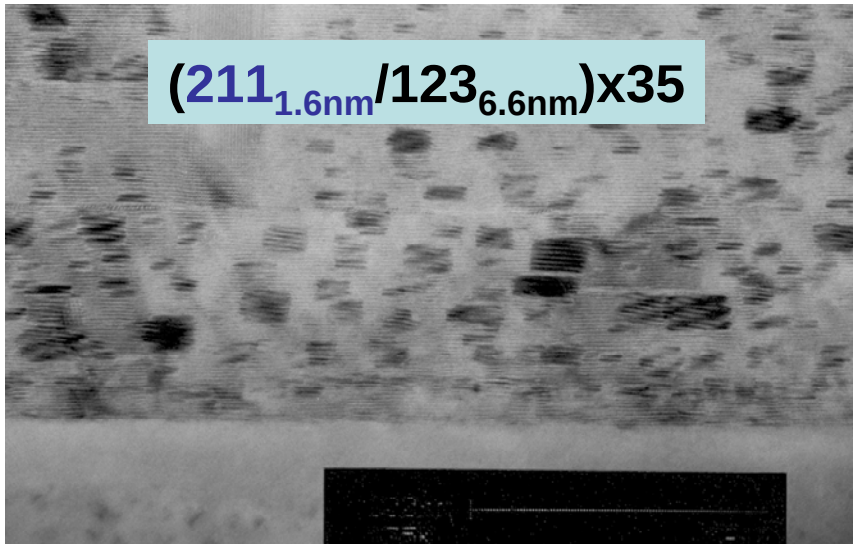
Formation of self-aligned nanodots and nanorods oriented along the c-axis of YBCO is perhaps a result of the heteroepitaxial growth along with large lattice mismatch for minimization of energy

Enhanced pinning is also obtained for 1 vol% $CaZrO_3$ and 2 vol% YSZ over pure YBCO



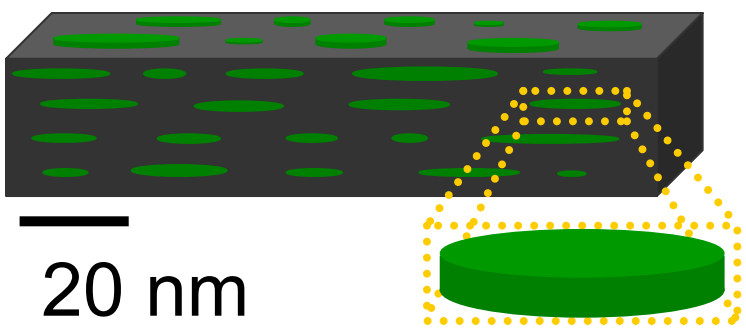


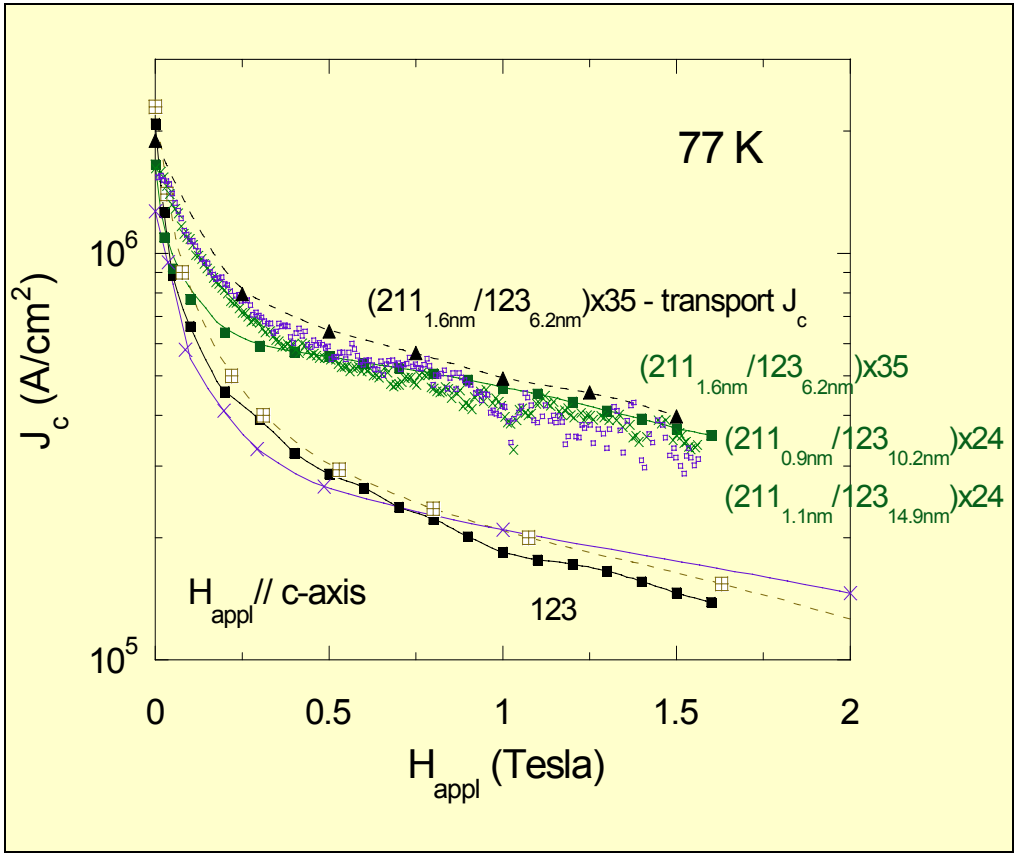
Pinning by 211 nano-particles in 211/123 multilayer films on RABiTS



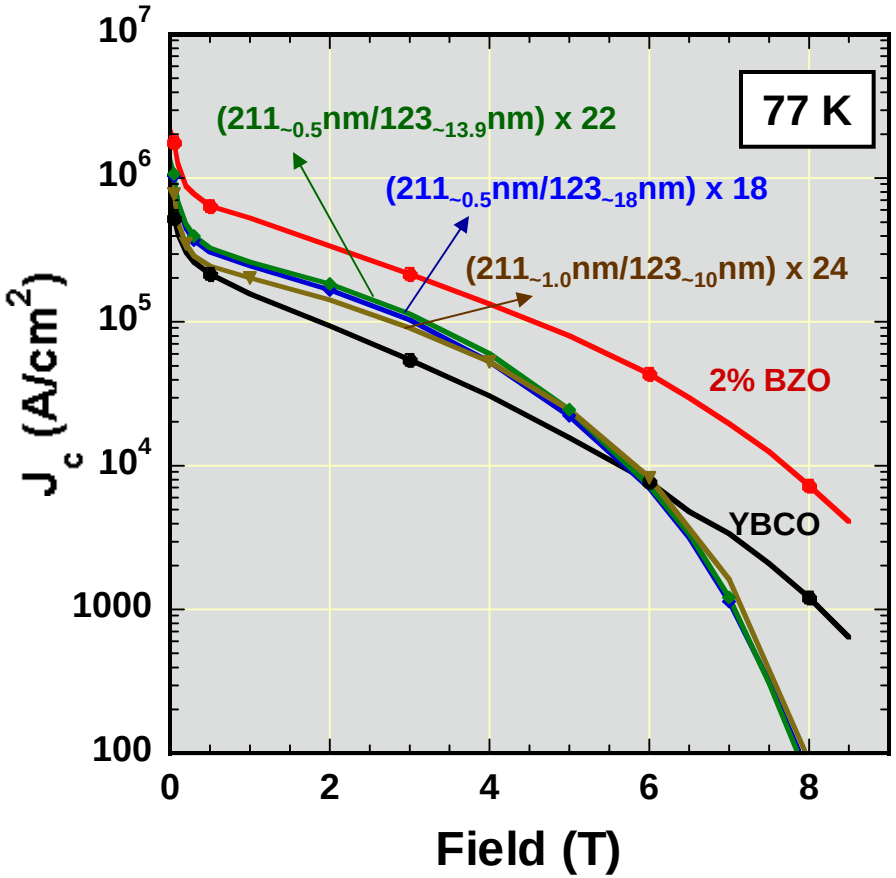
Particle Density ~ $3x10^{11}$ cm^{-2}

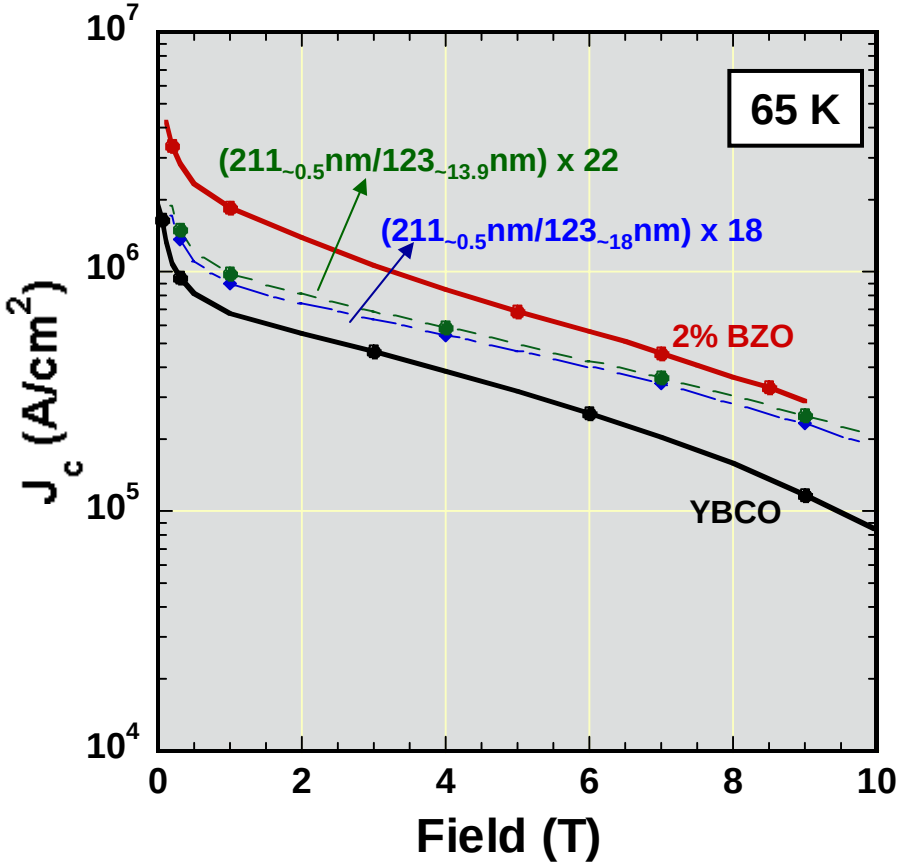
"Island growth of Y_2BaCuO_5 nanoparticles in $(211_{\sim 1.5nm}/123_{\sim 10\ nm})xN$ composite multilayer structures to enhance flux pinning of $YBa_2Cu_3O_{7-\delta}$ films", T. Haugan, P. N. Barnes I. Maartense, C. B. Cobb, E. J. Lee, M. Sumption, J. Mater. Res. 18, 2618 (2003) - Nov. issue.



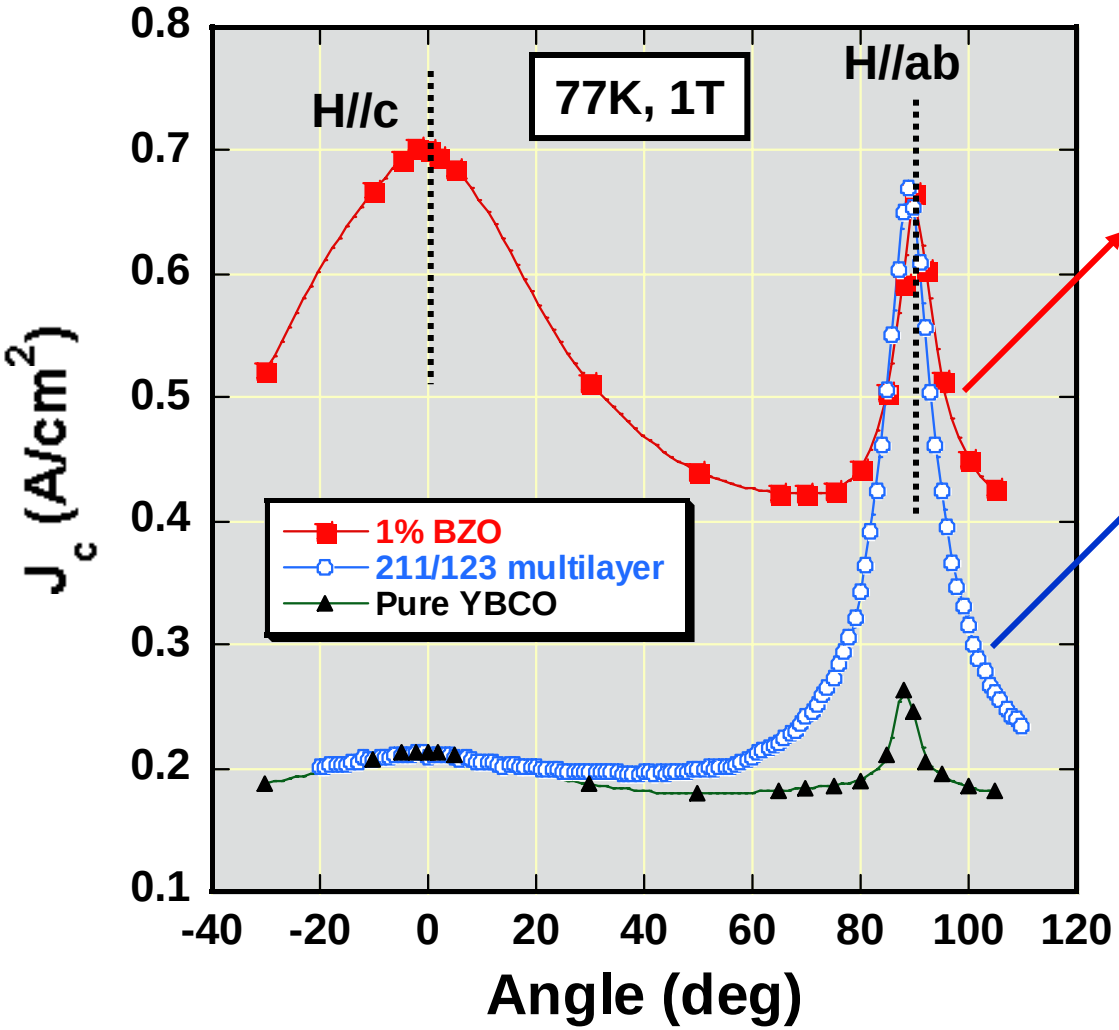


BZO nanodot/rod compared to pinning by 211 nano-particles for YBCO films on RABiTS





Angular dependence of J_c for 211/123 multilayer films on RABiTS



c-axis correlated pinning by extended defects + random pinning

random pinning by 211 particles

Summary

- Linear defects comprised of self-aligned nanodots and nanorods oriented along the c-axis of epitaxial YBCO films was shown possible for the first time
- These linear defects including the aligned misfit edge dislocations around the nanodots and nanorods result in significant pinning for H//c
- Best properties were observed in the range of 1-2 vol% BZO in YBCO
- Enhanced flux-pinning was also observed for CZO and YSZ additions
- Incorporation of 211 nano-particles in YBCO on RABiTS by deposition of 211/123 multilayers in collaboration with AFRL was also shown to result in enhanced properties

FY 2004 Plans and Performance

FY2004 Plans

- Develop all-solution buffer architectures that are compatible with ex-situ / MOD YBCO processes
  - Achieve over 200 A/cm-w on solution LZO seeds
  - Extend to 4-cm-wide substrates
- Continue fundamental studies of epitaxial growth solution buffers on textured substrates

FY2004 Performance

- ✓ High quality LZO and CeO_2 films were produced using solution deposition
- ✓ Nucleation and growth kinetics of solution processed LZO and CeO_2 layers were studied
- ✓ Achieved I_c of 213 A/cm-w on LZO seed layers using MOD YBCO
- ✓ Demonstrated I_c of 140 A/cm-w on an all-solution LZO/CeO_2 buffer architecture using MOD YBCO
- ✓ Demonstrated epitaxy of LZO on 4cm wide Ni-3at%W via dip-coating (data not shown but available for review)

FY 2004 Plans and Performance

FY2004 Plans

- Continue fundamental studies of epitaxial growth of PVD buffers on textured substrates
- Develop a fully conductive buffer architecture on copper-based substrates
- Achieve high-*I*c on copper substrates by *in-situ* or *ex-situ* approaches

FY2004 Performance

✓ Established feasibility of using metallic iridium (Ir) buffer layers for cation/oxygen diffusion barriers

✓ Developed a fully conductive simple buffer architecture of $La_{0.7}Sr_{0.3}MnO_3$/Ir on Ni-W tapes producing high-J_c PLD YBCO

✓ Developed a buffer layer stack of $CeO_2/La_{0.7}Sr_{0.3}MnO_3$/Ir for compatibility with *ex-situ* (BaF_2)

✓ Implemented $La_{0.7}Sr_{0.3}MnO_3$/Ir buffers on copper tapes as a fully conductive interface, yielding good J_c performance for PLD YBCO

✋ Deferred to next FY year due to reduced budget and work scope

FY 2004 Plans and Performance

FY2004 Plans

- Enhance flux-pinning in YBCO films on RABiTS through growth-controlled pinning centers

FY2004 Performance

- ✓ Linear defects comprised of self-aligned nanodots and nanorods oriented along the c-axis of epitaxial YBCO films was shown possible for the first time
- ✓ These linear defects including the aligned misfit edge dislocations around the nanodots and nanorods result in significant pinning for H//c
- ✓ Enhanced flux-pinning was also observed for BZO, CZO and YSZ additions
- ✓ Incorporation of 211 nano-particles in YBCO was also shown to result in enhanced properties

FY2005 Plans

- Continue development of functional buffer layers on textured non-magnetic substrates, including copper and copper alloys
- Determine feasibility cube-textured Cu-alloys with a yield strength of over 100 MPa and a conductivity of at least 50% IACS
- Establish viability of a fully conductive buffer architecture that is compatible with *ex situ* YBCO
- Further develop all-solution buffers and demonstrate J_c performance similar to that possible on vapor-deposited buffers
- Continue optimization of flux pinning in YBCO *in-situ* and *ex-situ* films on RABiTS:
  - Incorporation of second-phase pinning centers
  - Development of growth defects from substrate surface modifications

Research Integration

Interaction with Universities

- **University of Tennessee:**
  - **Tolga Aytug, S. Sathyamurthy: Research Assistant Professors working full time at ORNL**
- **University of Tennessee: J. R. Thompson / H. Weinstock (AFOSR)**
  - **A. O. Ijaduola, Ph.D. Dissertation work at ORNL**
- **University of Houston: K. Salama / H. Weinstock (AFOSR)**
  - **M.S. Bhuiyan, Ph.D. Dissertation work at ORNL**
- **University of Florida: D. P. Norton/ H. Weinstock (AFOSR)**
  - **K. Kim, Ph.D. Dissertation work at ORNL**

Research Integration

Interaction with Universities (continued)

- **University of Wisconsin, Madison: Eric Hellstrom**

  - Student working during summer at ORNL

- **University of California, Santa Barbara: Fred Lange**

  - Student pursuing Ph.D, one post-doc

- **University of Missouri-Rolla: Jay Switzer**

- **University of Houston: Alex Ignatiev**

- **University of Kansas: Judy Wu**

Close collaboration on DOE funded proposal

Summer Interns:

- **Jennifer Williams**, Carter High School Teacher, **Laboratory Science Teacher Professional Development Program**
- **Nicolas Cunningham**, Middle Tennessee State University, **Research Alliance in Math and Science for Minorities**
- **Erin Stewart**, Indiana University of Pennsylvania

Research Integration

Interaction with Companies

- American Superconductor Corporation
  - sample exchanges, joint characterization/evaluation
- 3M: Dick Ericson

Interaction with National Laboratories

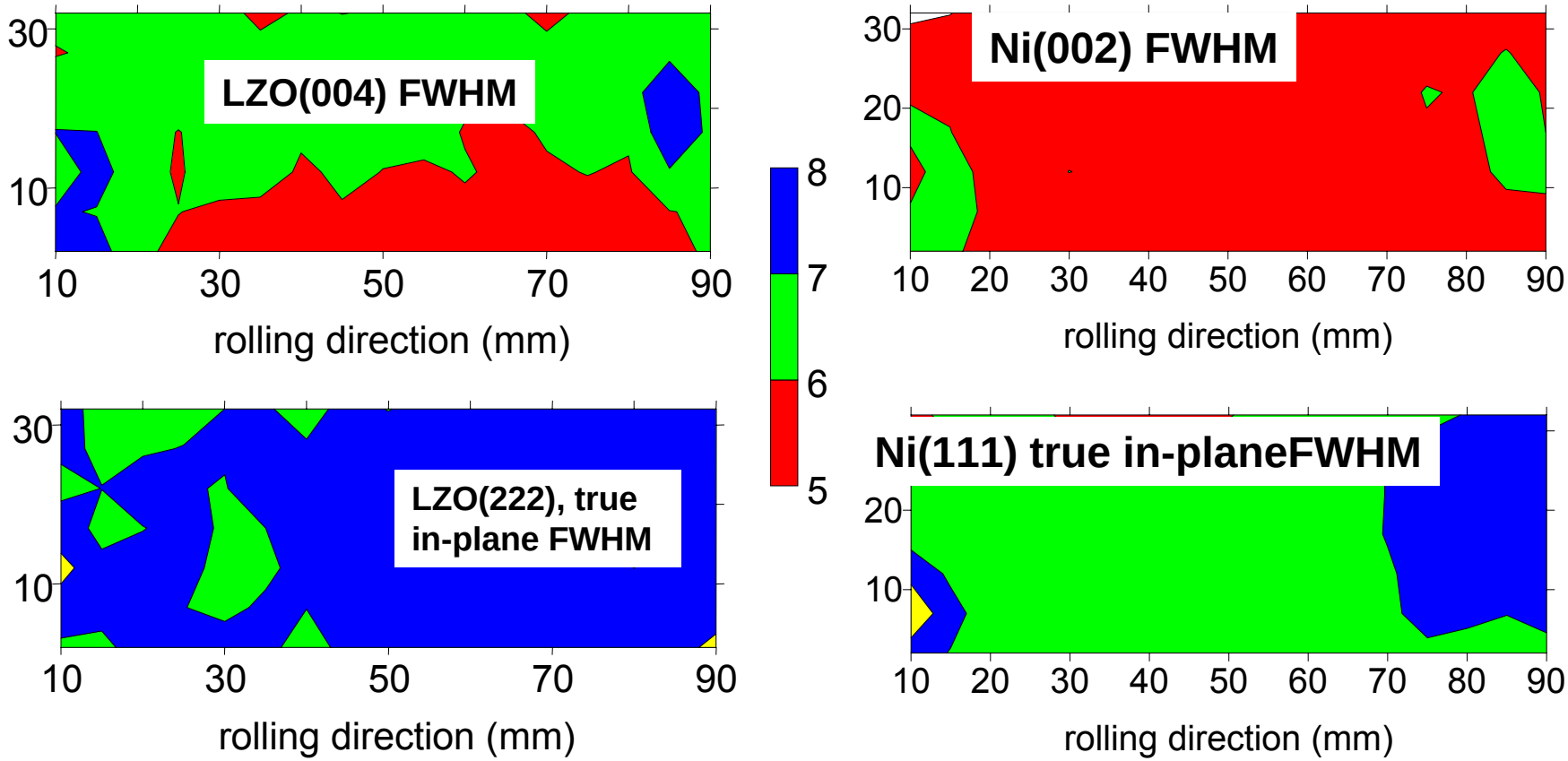
- Air Force Research Laboratory: T. Haugan, P. Barnes
- Sandia National laboratory: Paul Clem
- National Renewable Energy Laboratory: Raghu Bhattacharya

Communications:

- Many publications
- Numerous presentations
- Several patents issued as well as filed
- Information also dispersed via CRADA teleconferences/meetings/annual reports

Extras

Epitaxial MOD LZO coatings were produced on 4 cm wide Ni-W substrates using a reel-to-reel dip-coating



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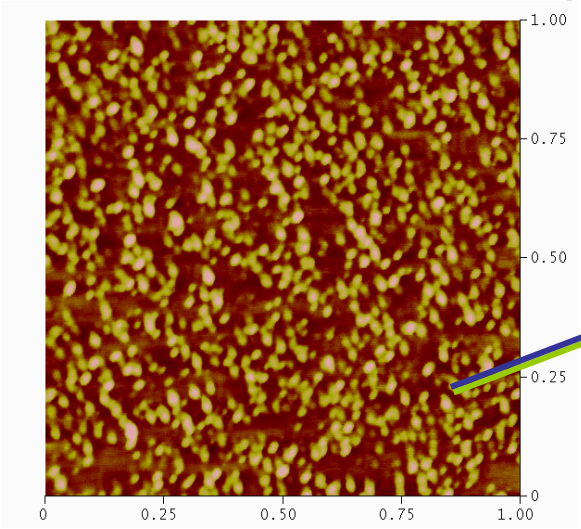
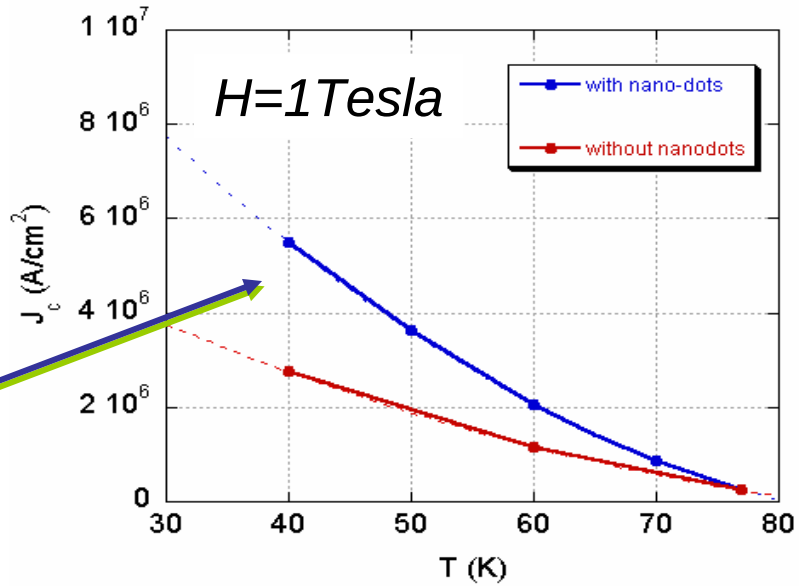
Growth of YBCO on nanodots

- *2D nanodot array grown on substrate surface*
- *YBCO (0.2μm) films deposited on the array*
- *2x enhancement of J_c*

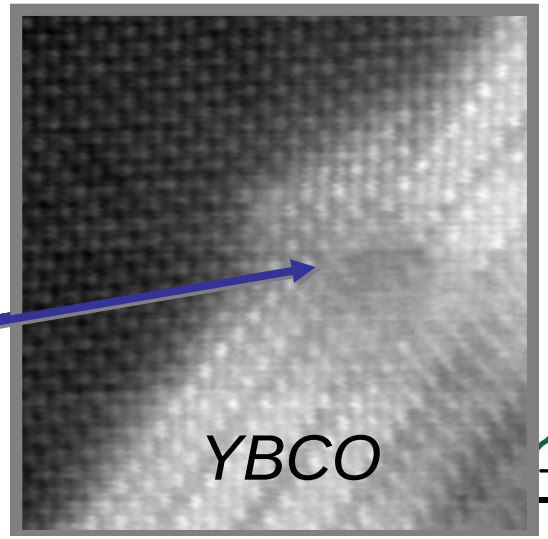
ZrO_2 nanodots (20 – 30 nm diam. x 3nm height)



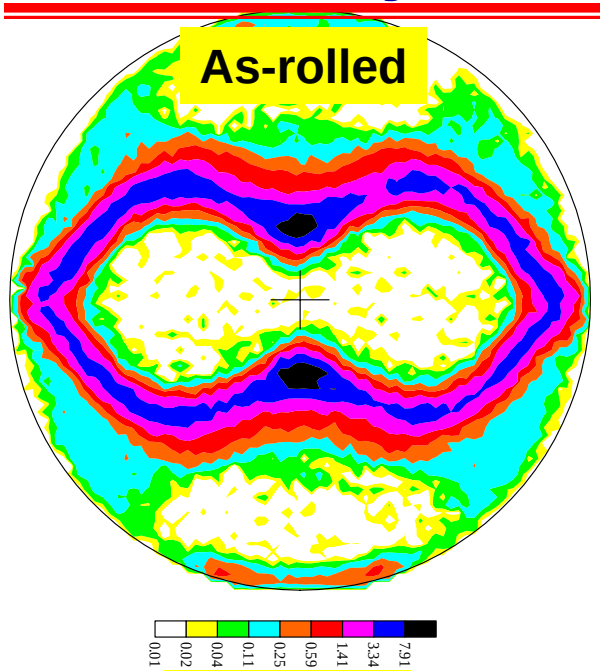


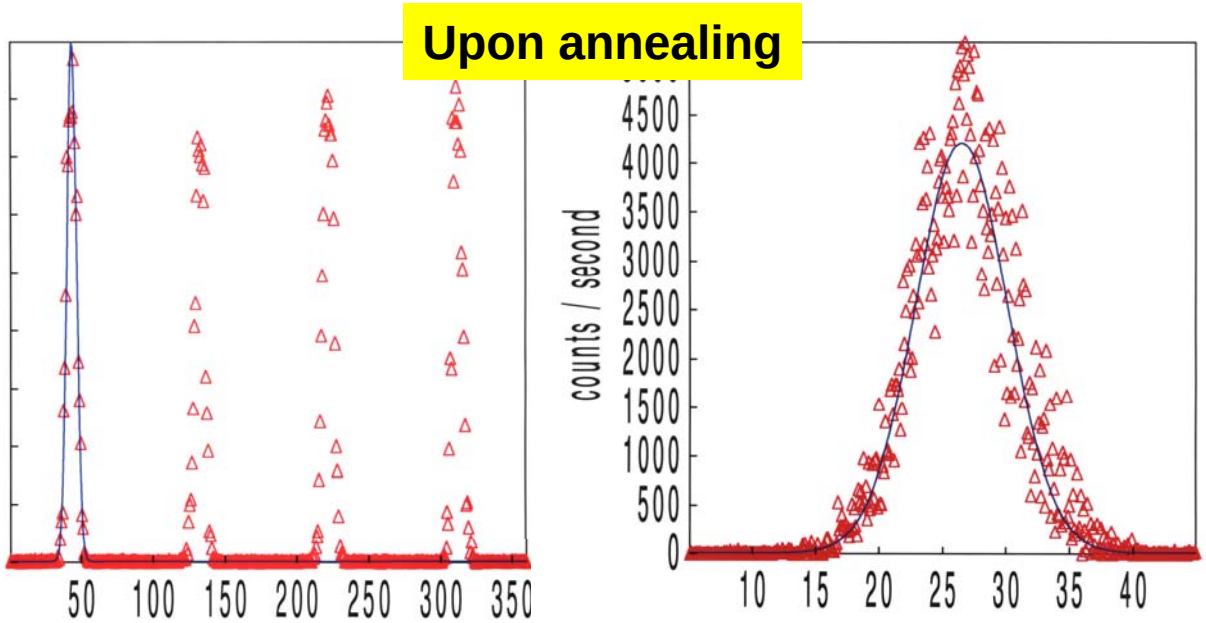
- **Mechanism as yet unconfirmed**

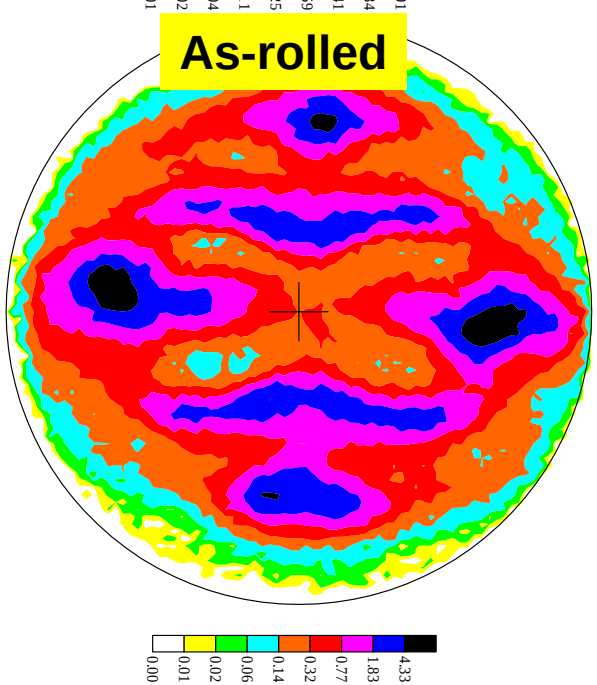
- **Speculate growth defects in YBCO nucleated atop dots**

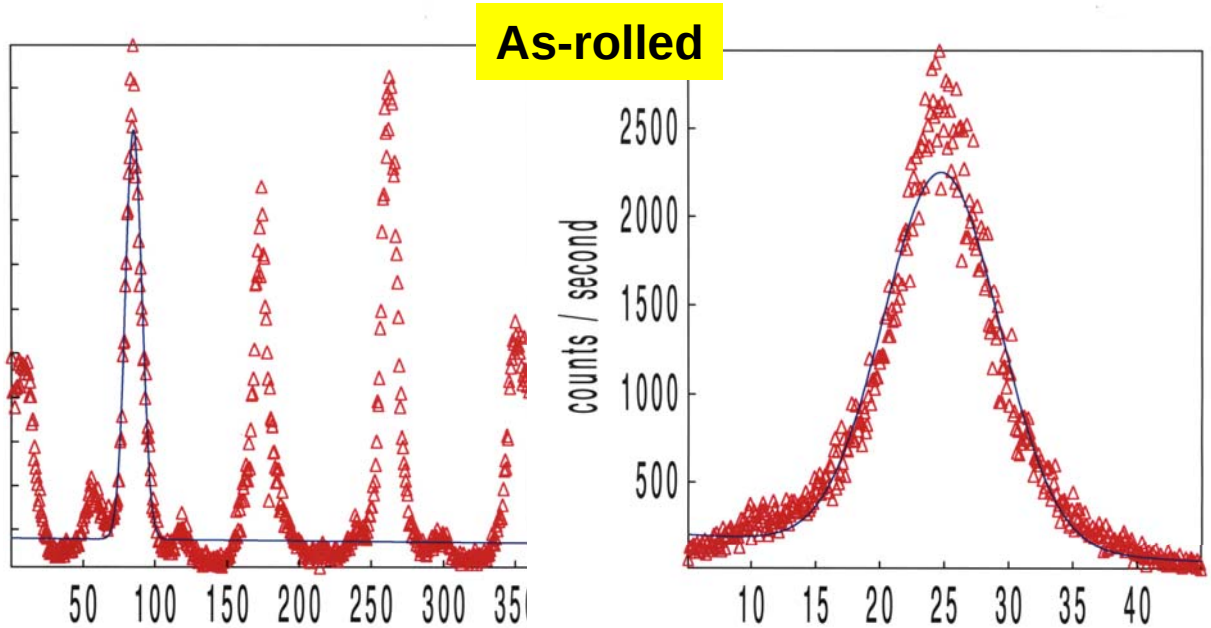


Cu Alloys: Biaxial texture in as-rolled alloys

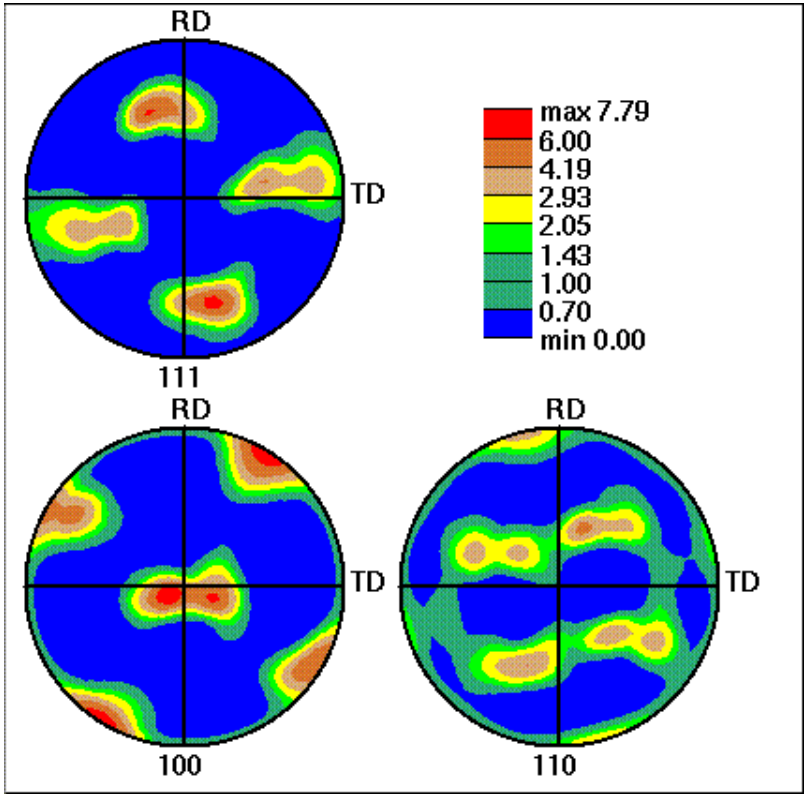


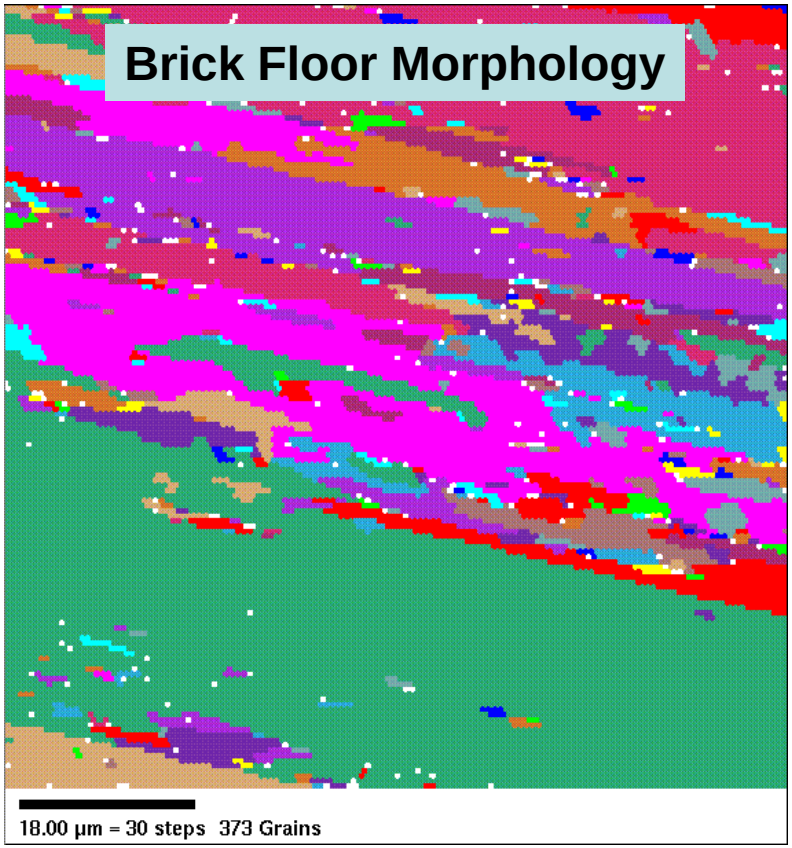






EBKP of surface of tape





Optimization of this texture could change the story with textured, strengthened Cu alloys with high conductivity

Cost of Iridium

	July, 2004	July, 2004	March, 2004	Blue sky
Ir price ($/troy oz)	200	200	100	100
Ir price ($/cc)	119.74	119.74	59.87	59.87
I_c (A/cm-width)	270	270	270	400
Ir thickness (cm)	1×10^{-5}	3×10^{-5}	1×10^{-5}	1×10^{-5}
Ir vol./kA-m (cc)	3.7×10^{-3}	1.11×10^{-2}	1.11×10^{-2}	2.5×10^{-3}
Ir cost/kA-m ($)	0.44	1.33	0.22	0.15

Cost of Ag overlayer

Ag: 6.5 $/troy oz
Ag price: 1.603 $/cc
I_c: 270 A/cm-width
Ag thick.: 3×10^{-4} cm
Ag vol./kA-m: 0.111 cc
Ag cost: 0.20 $/kA-m

Cost of Ni substrate

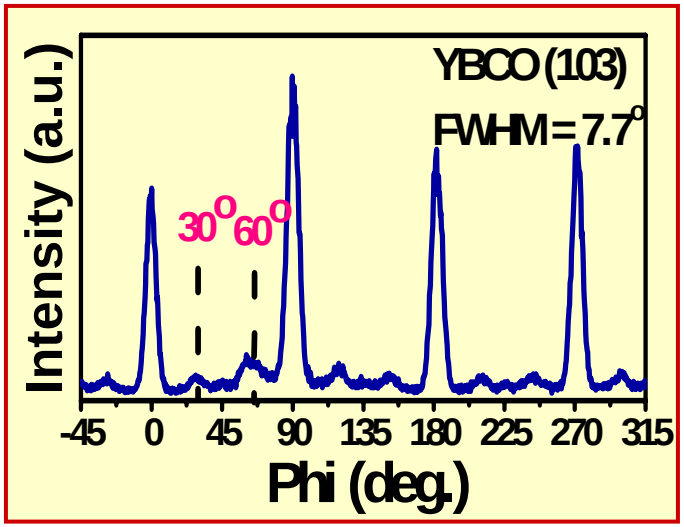
Ni-alloy: 20 $/lb
Ni price: 0.393 $/cc
I_c: 270 A/cm-width
Ni thickness: 5×10^{-3} cm
Ni vol./kA-m: 1.85 cc
Ni-alloy: 0.73 $/kA-m

Cost of Cu substrate

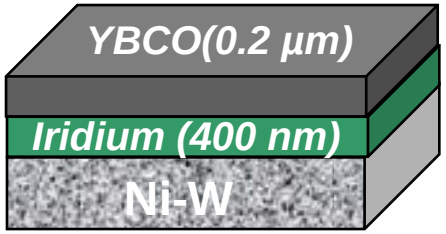
Cu: 1.12 $/lb
Cu price: 0.022 $/cc
I_c: 270 A/cm-width
Cu thick.: 5×10^{-3} cm
Cu vol./kA-cm; 1.85 cc
Cu cost: 0.04 $/kA-m

YBCO Films Directly on Ir

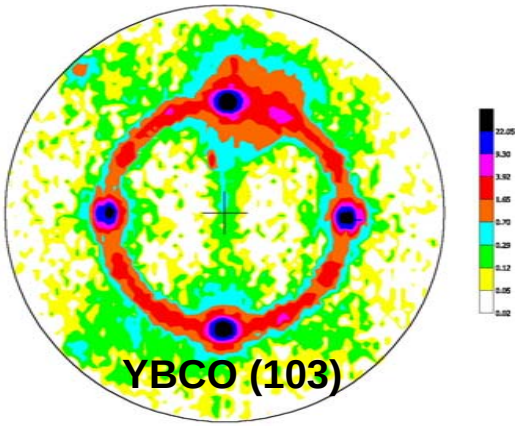
Limited J_c performance is due to the multiple domain oriented YBCO



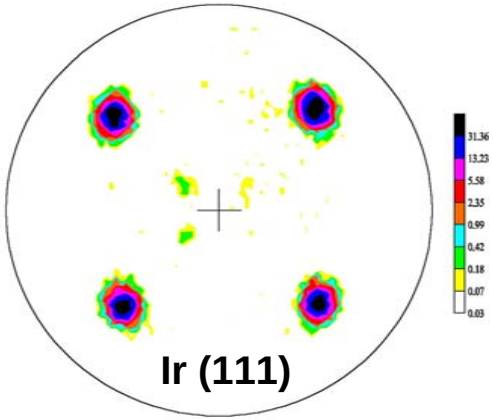
J_c(77 K) = 1.25 X 10^5 A/cm^2



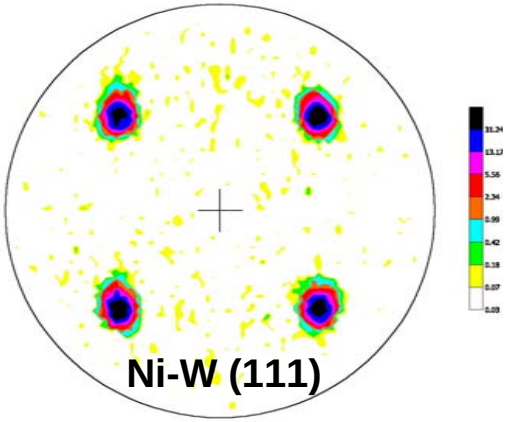
Cube % = 77

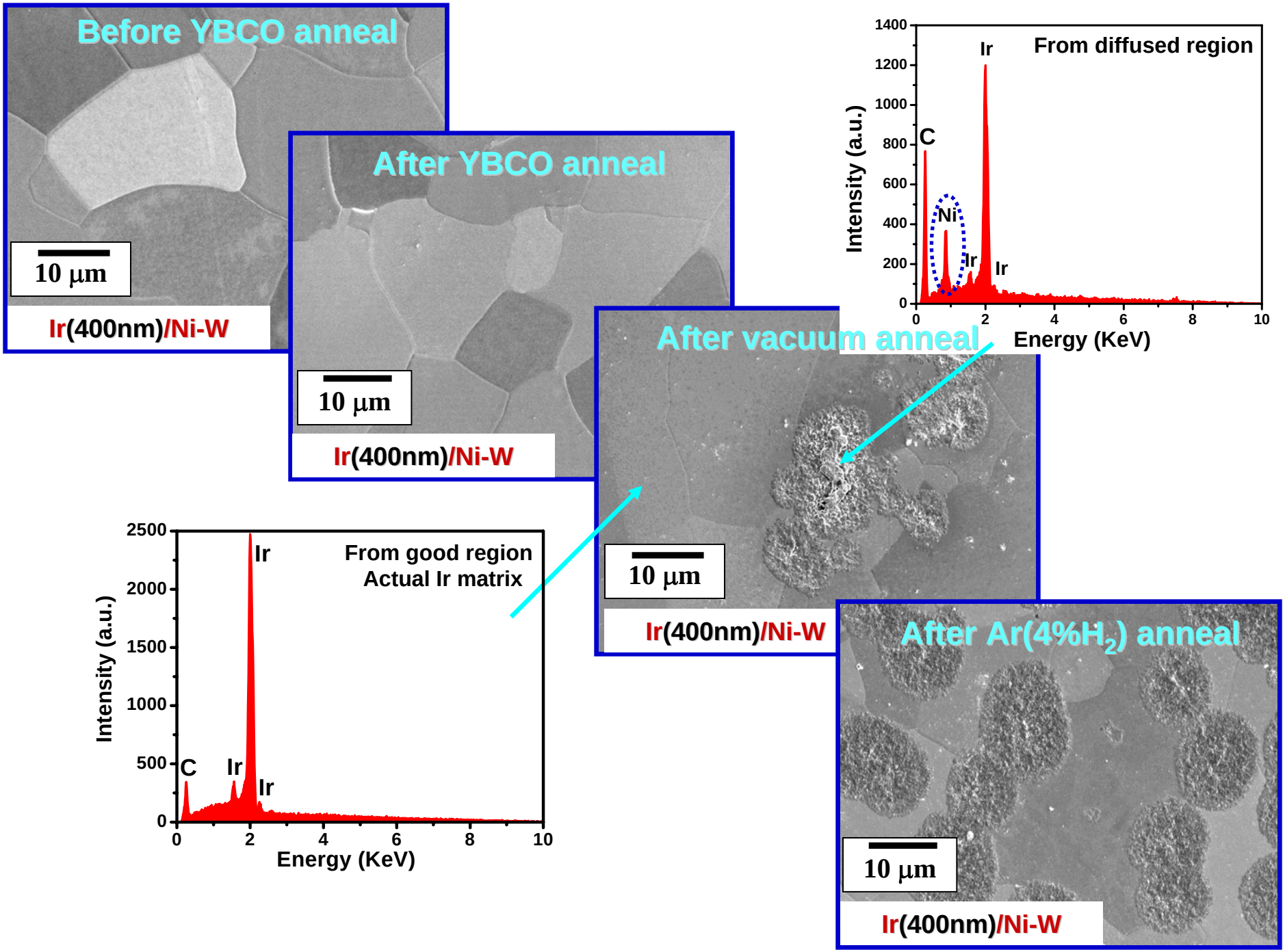


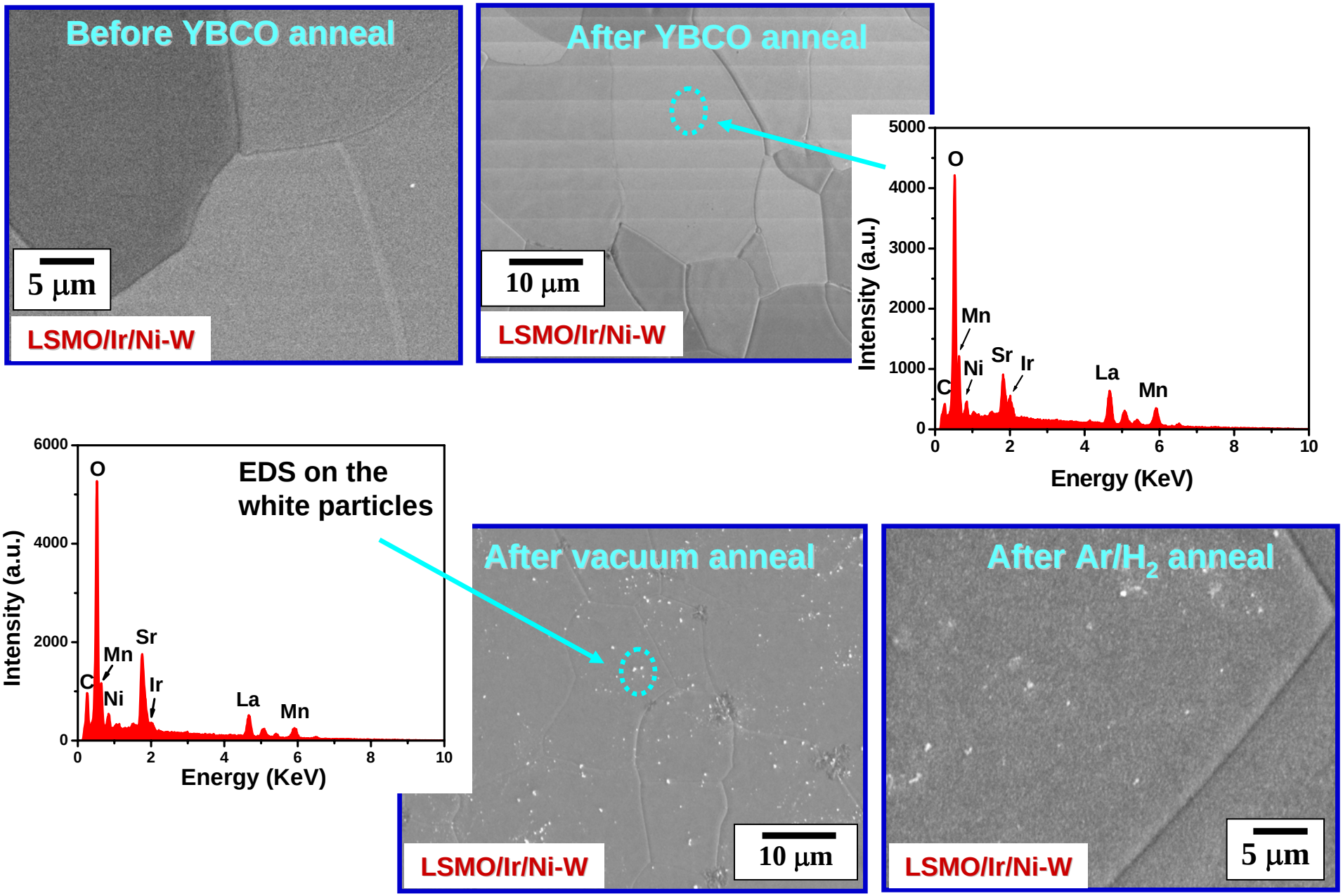
Cube %=98.6



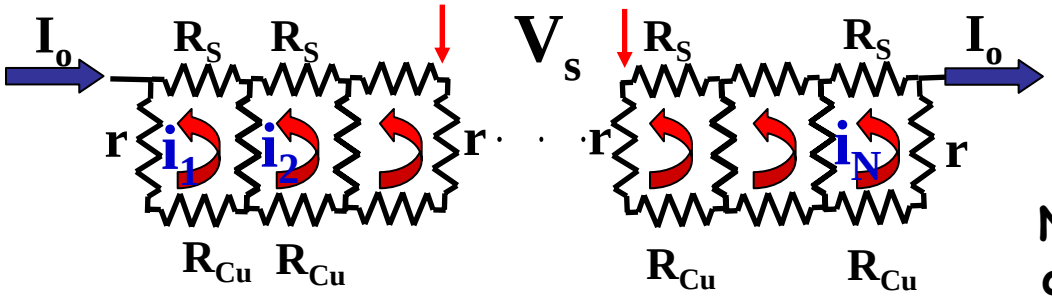
Cube % = 98.2



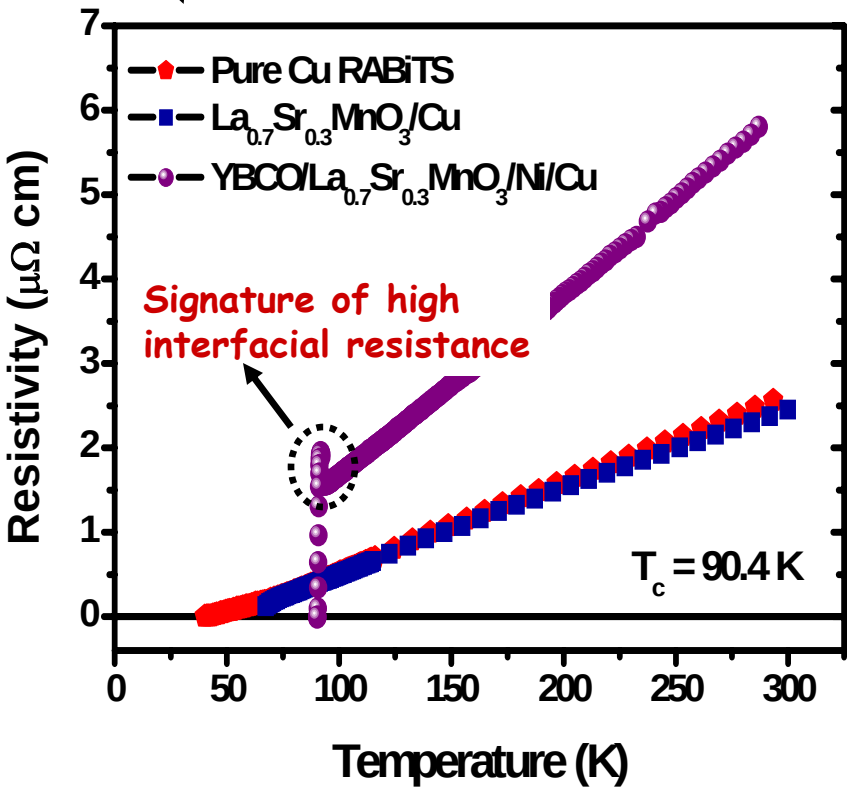

Before YBCO anneal
10 μm
Ir(400nm)/Ni-W
After YBCO anneal
10 μm
Ir(400nm)/Ni-W
After vacuum anneal
10 μm
Ir(400nm)/Ni-W
After Ar(4%H2) anneal
10 μm
Ir(400nm)/Ni-W
From diffused region
Intensity (a.u.)
Energy (KeV)
C
Ni
Ir
Ir
Ir
From good region
Actual Ir matrix
Intensity (a.u.)
Energy (KeV)
C
Ir
Ir
Ir


Before YBCO anneal
5 μm
LSMO/Ir/Ni-W
After YBCO anneal
10 μm
LSMO/Ir/Ni-W
Intensity (a.u.)
Energy (KeV)
O
Mn
Ni
Sr
Ir
C
La
Mn
EDS on the white particles
After vacuum anneal
10 μm
LSMO/Ir/Ni-W
After Ar/H2 anneal
5 μm
LSMO/Ir/Ni-W

Electrical Coupling Degrades due to Interfacial NiO Formation



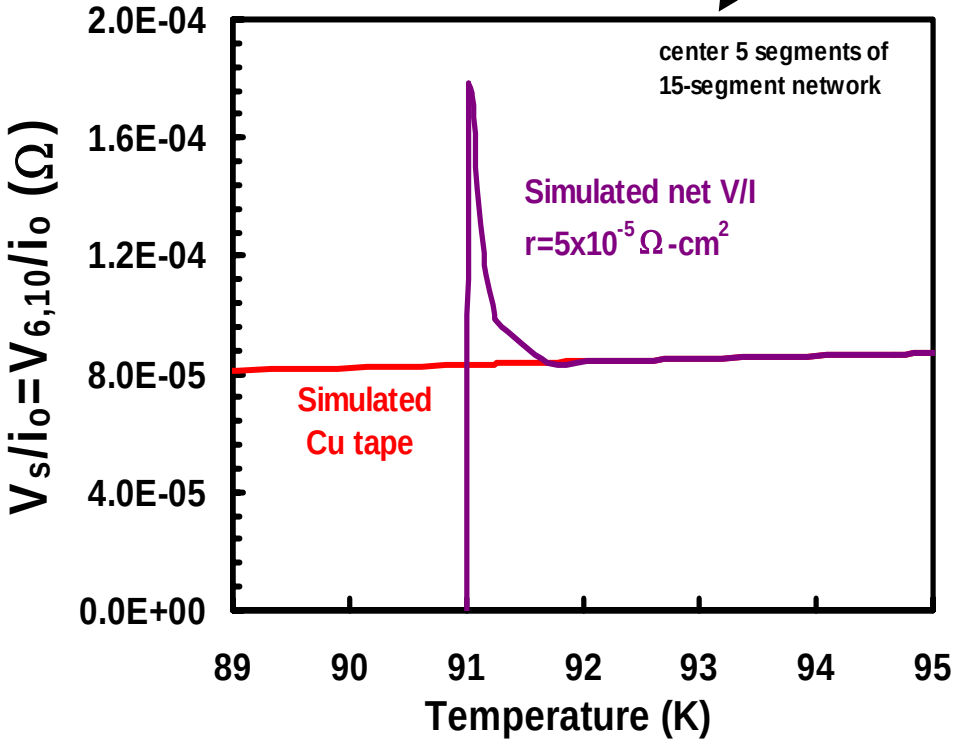
Actual sample



R vs T indicates contact barrier.
NiO causes poor interfacial resistivity.

Discrete model

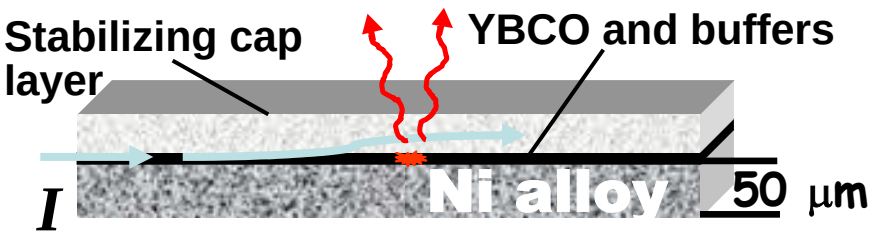
Numerical simulation of resistive network



Incremental decrease in R_s is more than compensated by the incremental inc. in current. → $dV = di*R_s + i*dR_s$, $dR_s=(-)$

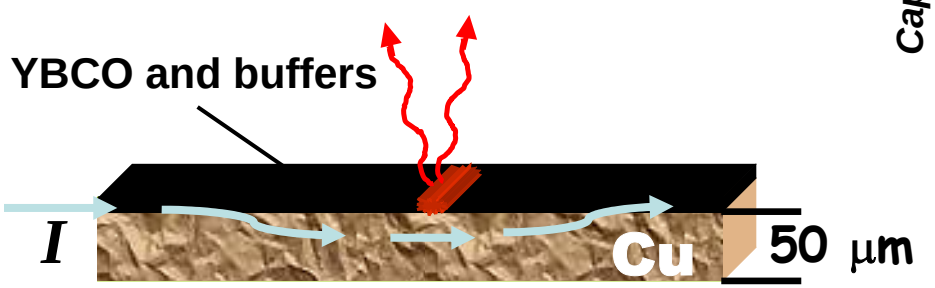
Conductive Buffer Layers: Intrinsic Stability

Stability is provided between the HTS coating and the metal substrate either by a conductive buffer or by a conductive cap layer.



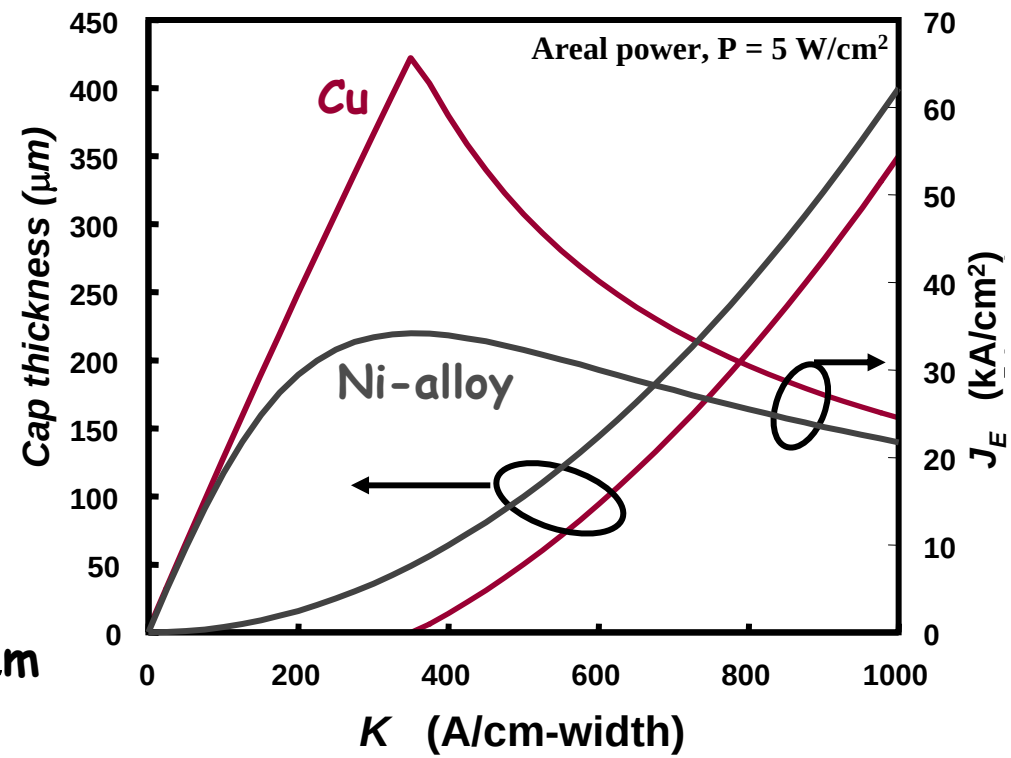
$J_E^{max} \approx 30 kA/cm^2$, $K^{max} \approx 400$ A/cm

metal cap layer 50 μm thick

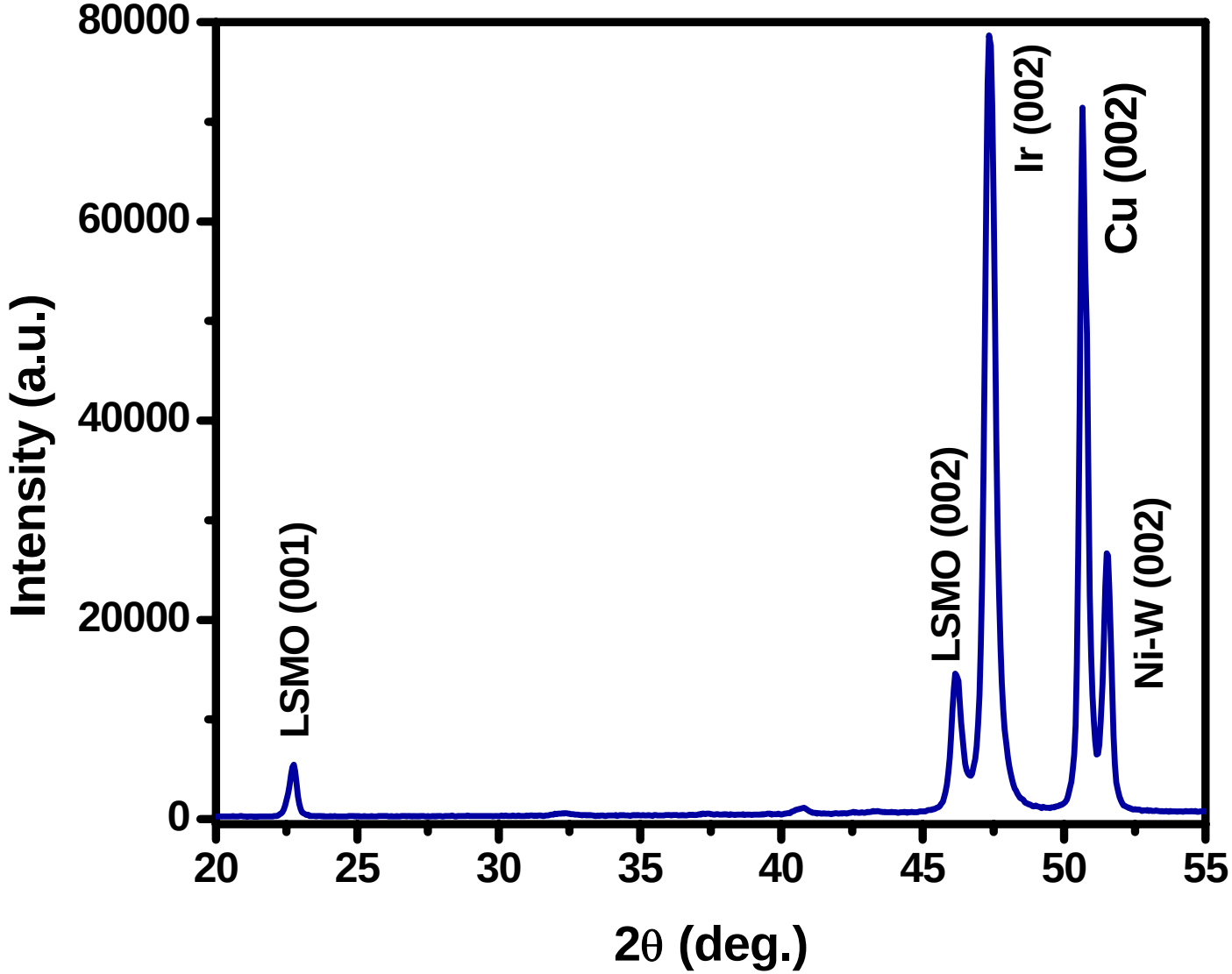


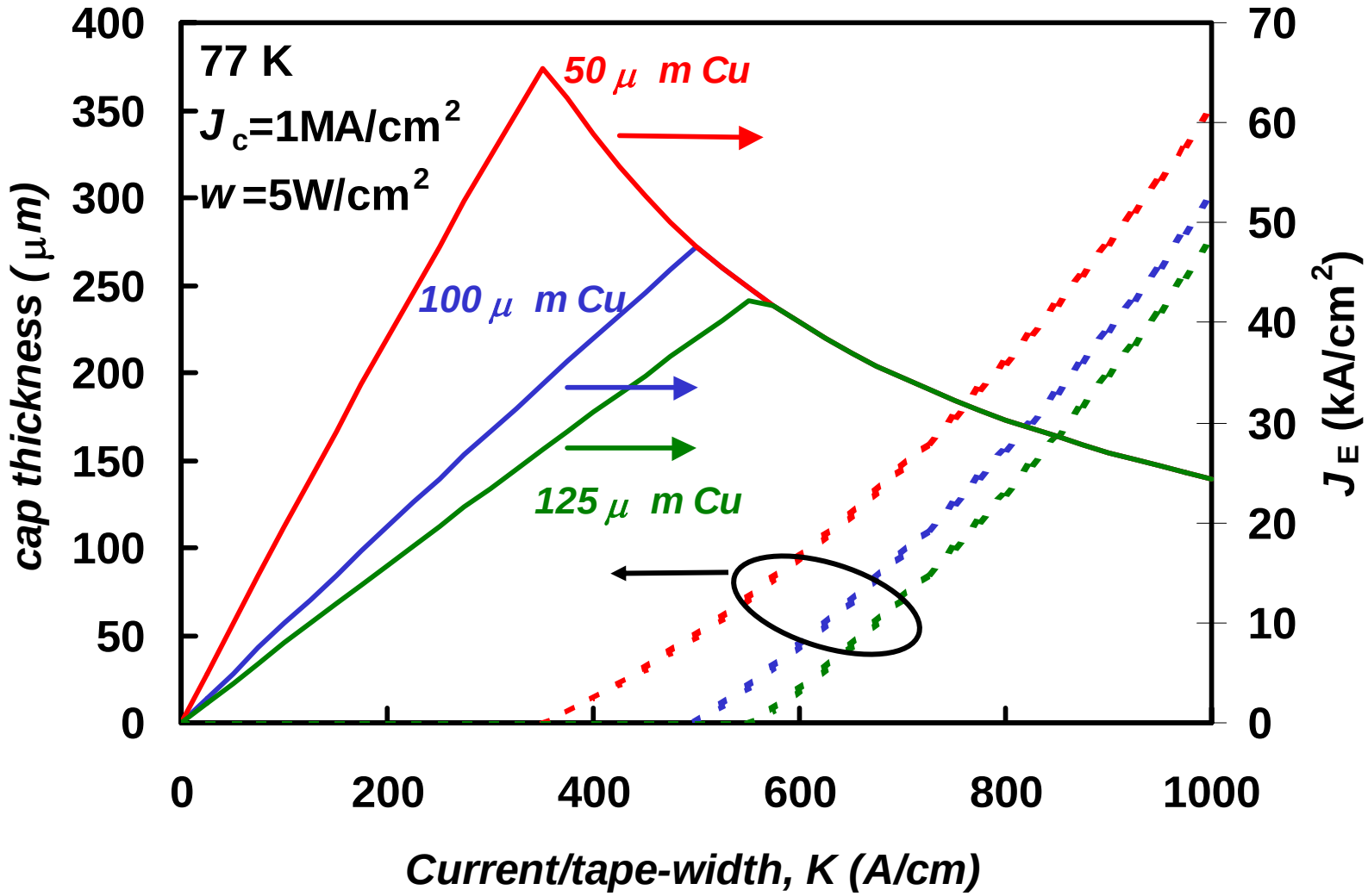
$J_E^{max} \approx 65 kA/cm^2$, $K^{max} \approx 400$ A/cm

No stabilizing cap layer needed



LSMO/Ir Architecture on Ni-9W/Cu



UT-BATTELLE

Stability Provided by Conductive Buffer Layers With Respect to Thickness of the *Cu* Substrate