Current limiting defects in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and YBa$_2$Cu$_3$O$_{7-x}$ films.

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Description of Samples

Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ (x≈0.08)

Epitaxial, grown *in situ* on [001]-tilt SrTiO$_3$ bicrystal by PLD process

≈350 nm thick

Coherence length

\[ \xi_{ab} = 2.44 \text{ nm} \]
\[ \xi_c = 1.22 \text{ nm} \]

\[ T_c \approx 18 \text{ K} \]

Samples for 4-point transport measurements
100 μm wide, 700 μm long links were patterned with laser ablation for 4-point transport measurements

Off-axis azimuthal θ-scans of the 112 reflections were used to define misorientation angles

In-plane misorientations: 3°, 5°, 9°, 24°
Do GBs in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ limit supercurrent?

**Description of Samples**

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- $\approx 350$ nm thick
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  - $\xi_{ab} = 2.44$ nm
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- Samples for 4-point transport measurements
  - 100 $\mu$m wide, 700 $\mu$m long
  - Links were patterned with laser ablation for 4-point transport measurements
- Off-axis azimuthal $\theta$-scans of the 112 reflections were used to define misorientation angles
- In-plane misorientations: $3^\circ$, $5^\circ$, $9^\circ$, $24^\circ$

**YBa$_2$Cu$_3$O$_{7-x}$**

- Coated conductors grown with e-beam BaF$_2$ *ex situ* ($\approx 350$ nm thick), PLD (0.5 $\mu$m) and MOD (1$\mu$m) processes on RABiTS
- $T_c = 89.7 - 90.0$ K
- Coherence length:
  - $\xi_{ab} \approx 2$ nm
  - $\xi_c \approx 0.4$ nm
- 3.5 $\mu$m – 6.6 $\mu$m wide
- 230 $\mu$m – 320 $\mu$m long
- Links were patterned with focused ion beam, then finished with laser ablation
- OIM was used to define misorientation angles
- In-plane and out-of-plane misorientations separated
- GBs have mixed misorientation
- Numerous low angle GBs studied
A superconducting track with inhomogeneity (i.e. all CCs) is put into the flux flow state, placing different areas at different points on their local I-V curve.

• A fine-focus laser beam probes the sample surface while simultaneously the electrical or/and optical response is recorded. The voltage difference $dV$ produced by the local heating of the laser beam is used to create a 2D image. It corresponds to the local 2D electric field $E$ distribution.
LTLSM vs. MO responses on YBCO test sample

Surface image

LTLSM voltage response
- $T=83$ K, $f_{\text{las}}=102$ kHz
- $I=379.7$ mA
- $V=157$ $\mu$V

MO ZFC image
- $T=10.4$ K
- $H_{\text{ext}}=40$ mT

$\delta V(x, y) \propto E(x, y)$

FIB cuts
- A: 40% of width
- B: 30% of width

250 nm thick YBCO

PLD YBCO film grown by G. Daniels;
FIB cut by S. Liao
MOI by A. Polyanskii
Bias current dependence of dV response $\text{Ba(Fe}_{1-x} \text{Co}_x)\text{As}_2$

Voltage response maps

1. $0.27 \, \mu V$ to $-0.08 \, \mu V$
2. $0.44 \, \mu V$ to $-0.07 \, \mu V$
3. $0.52 \, \mu V$ to $-0.07 \, \mu V$

Critical current density of the bottom grain is smaller possibly due to strain.

$9^\circ \text{GB}$
$T=12 \, \text{K}$
$B=3.5 \, \text{T}$

Red points are bias points for LTLSM visualization.

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$100 \, \mu \text{m}$

Current, mA

$0 \, \mu V$ to $70 \, \mu V$
Bias current dependence of dV response Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$

Even 3$^o$ GB is current limiting

$J_{c\ GB} / J_{c\ bulk} \geq 0.93$

$3^o$ GB
$T=12$ K Self-field

Red points are bias points for LTLSM visualization.
Visualization of transition from GB to IG behavior in Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$ on 5° bicrystal

Redistribution of electric field

Similar to YBCO: $R_{ff}$ rising above the transition field

$T=16.5$ K

Small average voltage kept constant by reducing the bias current to get the same average electric field.

dV near GB is decreasing as $B$ rising (similar to YBCO)

$I_{bias}$

-0.09 μV 0.28 μV $<V> \approx 2$ μV 100μm

$B$, Tesla

$R_{ff}$, mΩ

Bias current, mA

$dV_{max}$, μV

$rac{dV}{dB}$, μV

Bias current, mA
Non-uniformity of the GB at 12 K for 5° GB

Pattern repeats for all measured fields: 0.25 T-5 T
$J_c$ of $3^\circ$ and $5^\circ$ GB match above 4T
$J_c$ decays exponentially in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ GBs

$$J_{c,gb}(\theta_r) \propto \exp(-\theta_r / 3.36)$$

$\theta_{rc} = 3.36^\circ$

T=12 K
0.5 T

Critical angle $\theta_{rc}$ is similar to YBCO grown on [001] tilted bicrystals
Conclusions on Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$

• For Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$ bias current dependencies and magnetic field dependence of $E(x,y)$ near GBs are qualitatively similar to previously found in YBa$_2$Cu$_3$O$_{7-x}$ Coated Conductors;

• Even 3° GB is current limiting;

• Self field critical angle (3.4°) for Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$ GBs is similar to in-plane misoriented MOD YBCO GBs;

• Found strong non-uniformity of the dV response along Ba(Fe$_{1-x}$ Co$_x$)$_2$As$_2$ GBs. To understand microscopic origins of these non-uniformities additional TEM analysis is necessary;
Which type of GB best carries current in YBCO?

Ex situ thick films have meandered GBs (MOD), in situ films have planar GBs (PLD)

Feldmann et al. (ASC): MOD meandered GBs are not exponential and can have higher $J_c$

Held et al.: [010] out-of-plane (OOP) GBs have higher $J_c$ than [001] in-plane (IP) tilt – planar PLD GBs on STO

Our aim: understand the nature of real GBs on RABiTS and the best way forward to higher $J_c$ with less current blocking
OIM + FIB + LTLSM make 1D GB arrays in well defined tracks

- **Samples with planar GBs:**
  1. Thin (0.34 μm) BaF₂ on older RABiTS \( (\Delta \omega \sim 5^\circ, \Delta \phi \sim 6^\circ) \)
  2. 0.55 μm thick PLD (ASC) on more modern RABiTS, OOP<IP \( (\Delta \omega \sim 2.5^\circ, \Delta \phi \sim 5^\circ) \)
  3. ~1 μm thick YBCO on modern RABiTS – \( (\Delta \omega \sim 7.5^\circ, \Delta \phi \sim 6.5^\circ \) for Ni substrate);  
- **Fully characterize sample with EBSD (orientation and GB maps)**
- **Cut 1D tracks with FIB**
  - Width: 3.4 μm - 6.2 μm;
  - Length up to ~370 μm
- **Low Temperature Laser Scanning Microscope (LTLSM)** images of the GB tracks in self field to 5T at variable bias to get \( I_c(H) \) of each GB
Ex situ BaF$_2$ on older AMSC RABiTS has similar a-axis and c-axis orientation maps
Ex situ BaF$_2$ on older ($\Delta\phi \sim 5$–$7^\circ$, $\Delta\omega \sim 5^\circ$) AMSC RABiTS has continuous network of OOP and IP GBs

~ 10 GBs per track
MOD on modern AMSC RABiTS ($\Delta \phi \sim 5.5^\circ$, $\Delta \omega \sim 3.8^\circ$) has low-angle orientation c-axis map and numerous low-angle GBs on out-of-plane misorientation map.

Rotation angle map

Many highly-misaligned grains

Few highly-misaligned grains
MOD on modern AMSC RABiTS ($\Delta \phi \sim 5.5^\circ$, $\Delta \omega \sim 3.8^\circ$) has low-angle orientation c-axis map and numerous low-angle GBs on out-of-plane misorientation map.

Many OOP GBs with up to 5° misorientation within substrate grains.
Each track has a complete correlation of GBs by SEM, OIM, and LTLSM.
Visualization of transition from GB to IG behavior in quasi-1D MOD YBa$_2$Cu$_3$O$_{7-x}$ link

Local electric field becomes more homogeneous as magnetic field rises

Magnetic field

0.5 T  0.75 T  1 T  1.5 T  1.75 T  2 T  2.5 T  2.75 T  3 T  3.5 T  4 T  5 T

Bias current

19.12 mA  17.25 mA  15 mA  13.54 mA  12.39 mA  10.87 mA  9.05 mA  8.14 mA  7.24 mA  6.0 mA  4.76 mA  3.03 mA

$\langle V \rangle = \text{const}$

8.8 $\mu$V

-0.15 $\mu$V

50 $\mu$m
Varying the bias current reveals the $I_c$ distribution

\[ \Delta P \rightarrow \Delta T(x_l, y_l) \rightarrow \Delta j_c \rightarrow \Delta V(x_l, y_l) \]

$I_c(x)$ defined at onset of local $E$
for BaF$_2$ 
*ex situ* YBCO film on RABiTS

GB numbered

Bias current

SEM

Th-P dV

LT dV

-0.28 μV

7.68 μV

1 Tesla

R, μm

0 50 100 150 200 250 300

0 2 4 6 8

0.17 mA

0.54 mA

0.89 mA

1.07 mA

1.97 mA

4.32 mA

5.05 mA

5.96 mA

7.59 mA

8.49 mA

9.21 mA
Bias current dependencies of dV responses at 1 T for GBs

BaF$_2$ ex situ YBCO film on RABiTS
Critical angle versus rotation angle for BaF$_2$ ex situ YBCO film on RABiTS

Grain current

\[ J_c(\Theta_r) = J_{c0} \exp \left( -\frac{\Theta_r - \Theta_{r0}}{\Theta_{rc}} \right) \]

\( \Theta_{r0} = 2.75^\circ \pm 0.01^\circ \)

\( \Theta_{rc} = 1.16^\circ \pm 0.03^\circ \)

The transition field \( B^* \) (at which grain \( J_c \) matches GB \( J_c \)) from linear fitting of dependence \( B(\Theta_{r0}) \) found:

\[ B(\Theta_r)^* \approx \Theta_r -2.4, \text{ where } B \text{ is in Tesla, } (\Theta_r \geq 2.4^\circ) \]
$J_c$ in meandered GBs does not decrease exponentially with GB rotation misorientation for MOD films

- No exponential dependence;
- $J_c$ up to 3 MA/cm$^2$ were measured

- $J_c$ was detected for 14 GBs
- Other low-angle GBs have higher $J_c$ therefore not measurable by LTLSM due to risk of burning links
- Two links were burned out
Separation of in-plane and out-of-plane components

No obvious difference between IP and OOP components for GB measured by LTLSM in self field.
Jc of individual MOD YBCO CC GBs at 0.5T

- More OOP components up to 5°, but they do not block super current;
- No GBs with OOP angle below 1 degree;
- Jc up to 1.2 MA/cm² were measured

\[
J_c \approx J_{co} \exp \left( -\frac{\Theta}{\Theta_c} - \frac{\Phi}{\Phi_c} \right)
\]

\(\Theta_c = 3.3°\) In-plane
\(\Phi_c = 19.65°\) Out-of-plane

![Graph showing Jc values with color scale and in-plane vs. out-of-plane angles](image)
$J_c$ has no obvious dependence on whether IP or OOP misorientation dominates

ex situ BaF$_2$ YBCO films on vintage RABiTS
Comparison of $J_c$ for different films at 2T, 79.2K

BaF$_2$ on older RABiTS

PLD on 1 yr old RABiTS

MOD on modern RABiTS

$\theta_c = 4.6^\circ$
$\Phi_c = 3.3^\circ$

$\theta_c = 3.06^\circ$
$\Phi_c = 2.99^\circ$

$\theta_c = 5.9^\circ$
$\Phi_c = 19.33^\circ$

Self-field: In-plane critical angle
$\theta_c = 3.3^\circ$
$\Phi_c = 19.65^\circ$

Out-of-plane critical angle
Conclusions – LTLSM study of YBCO GBs

• Used synergy of OIM, SEM (FIB) and LTLSM to measure $J_c$ of individual GBs
• Our approach allows better statistics than other techniques
• For MOD CC we studied 62 naturally occurring GBs - they displayed dominant OOP misorientation
• For MOD CC IP component reduces $J_c$ more than OOP component (between 1°-5°)
• IP and OOP misorientation components of BaF$_2$ on older RABiTS reduce $J_c$ similarly
• Self field $J_c > 3$ MA/cm$^2$ were measured for several GBs at 79.2K on MOD CC
• Meandering GBs of modern MOD film on RABiTS have larger $J_c$ than PLD on RABiTS and BaF$_2$ on older RABiTS